Experimental Overview on GPDs and TMDs

International Nuclear Physics Conference
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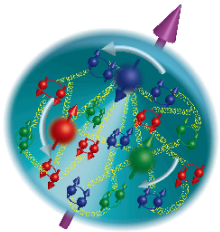
Duke UNIVERSITY

昆山杜克大学 DUKE KUNSHAN UNIVERSITY

Nucleon Spin Decomposition



Proton spin puzzle

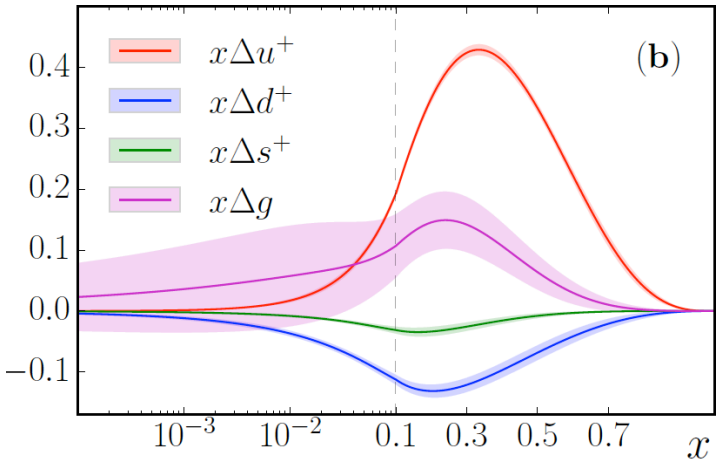
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

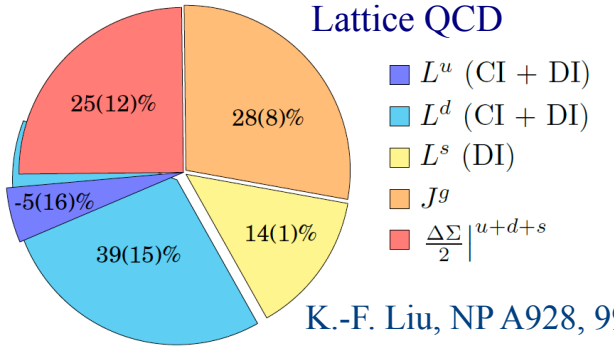
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



JAM Collaboration, PRD 93, 074005 (2016).



K.-F. Liu, NP A928, 99 (2014).

Access to $L_{q/g}$

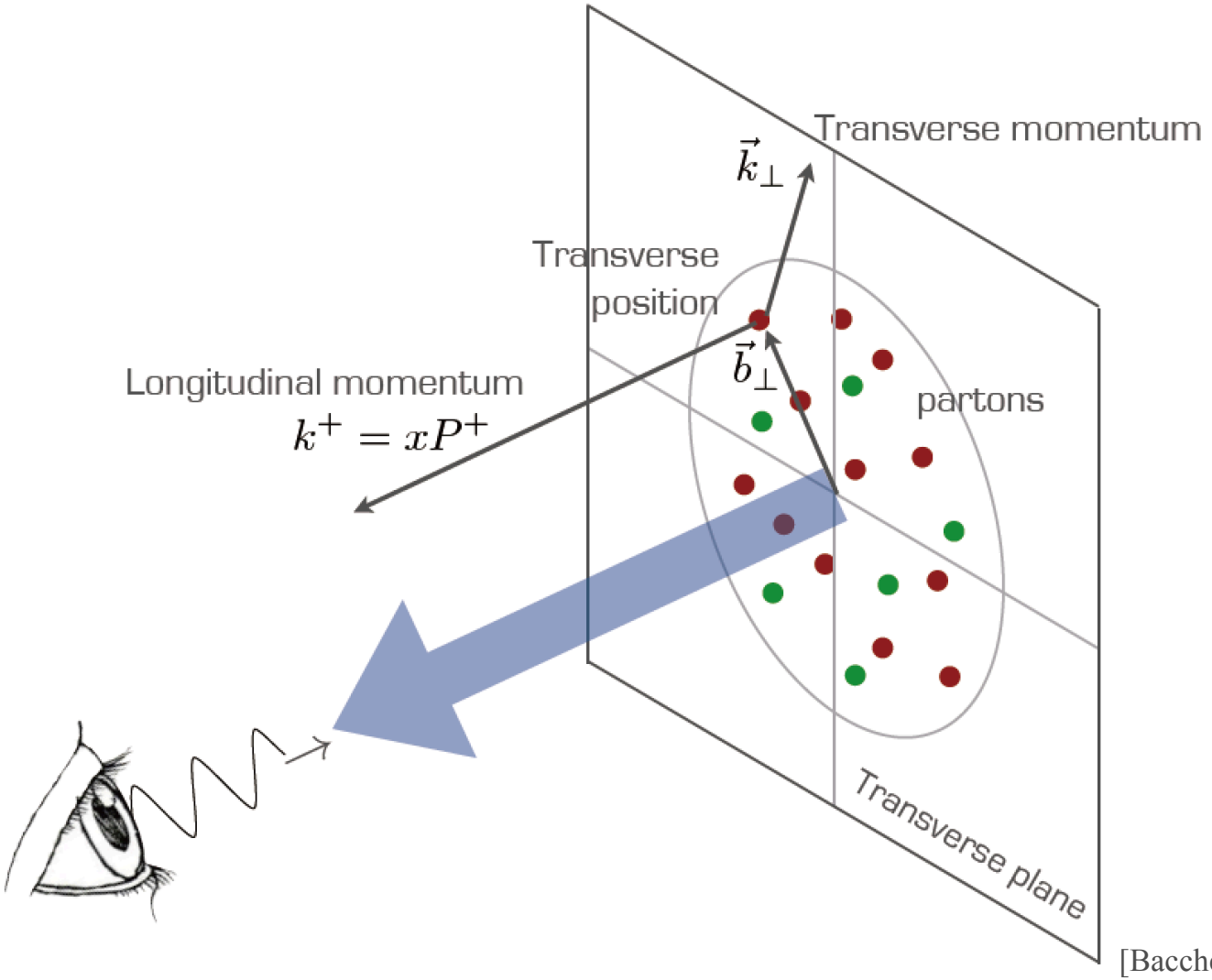
It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Carl Gagliardi (R7 Tuesday)

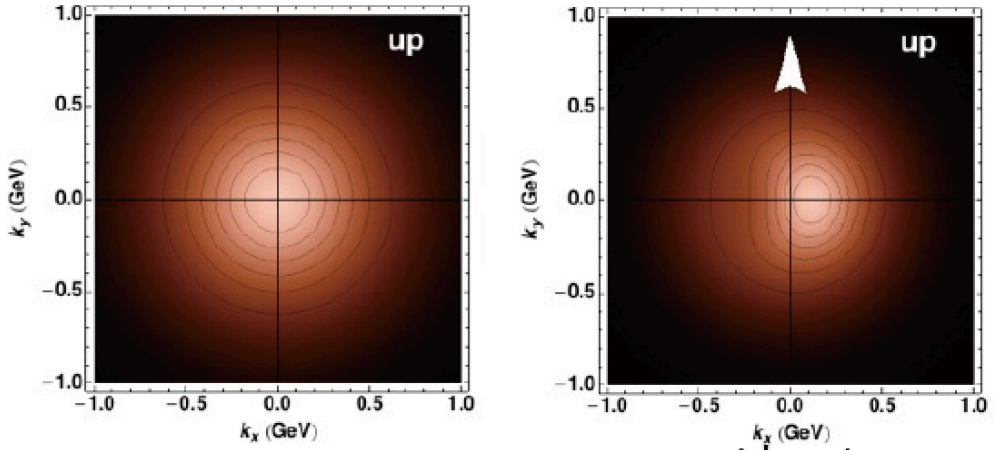
Nucleon Structure from 1D to 3D



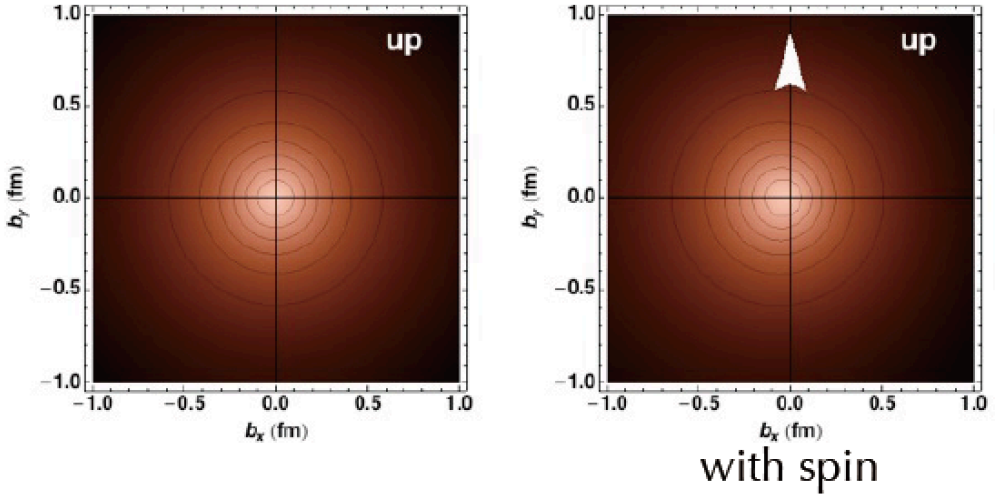
[Bacchetta's talk (2016)]

Nucleon Structure from 1D to 3D

Transverse momentum distributions:
TMDs



Impact parameter distributions:
Fourier transf. of
GPDs



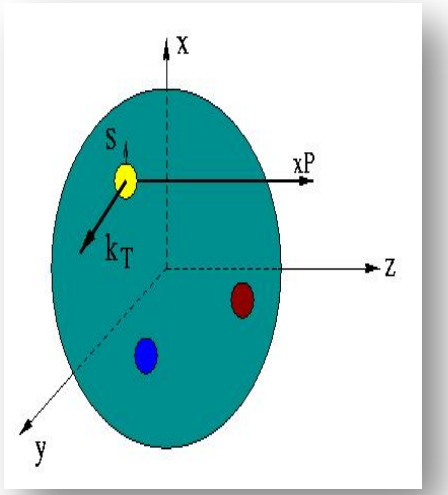
Silvia Niccolai (Thursday plenary)

[Bacchetta's talk (2016)]

Unified View of Nucleon Structure

$W_p^u(x,k_T,\boldsymbol{r_T})$ Wigner distributions

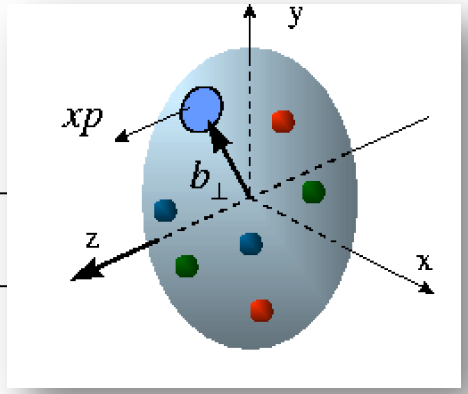
5D Dist.



$d^2\boldsymbol{r_T}$ d^2k_T

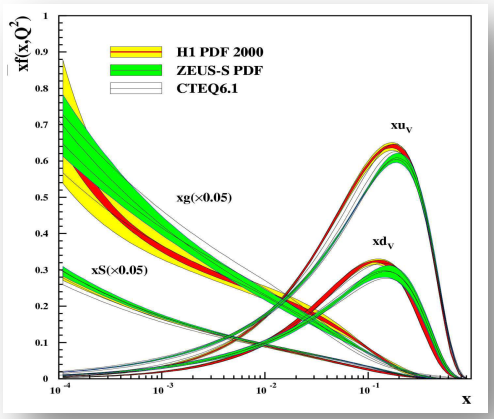
TMD PDFs
$f_1^u(x,k_T)$, ..
$h_1^u(x,k_T)$

GPDs/IPDs



3D imaging

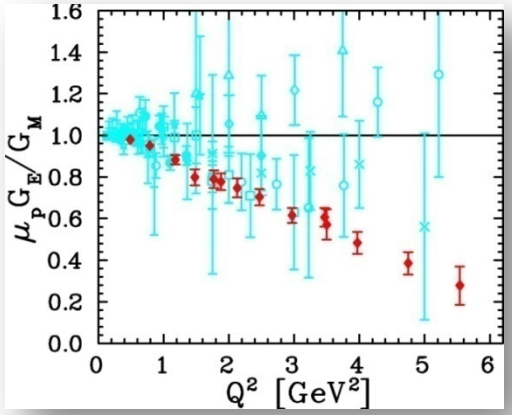
d^2k_T d^2r_T dx & Fourier Transformation



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

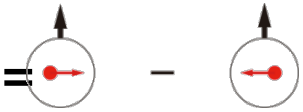
Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$



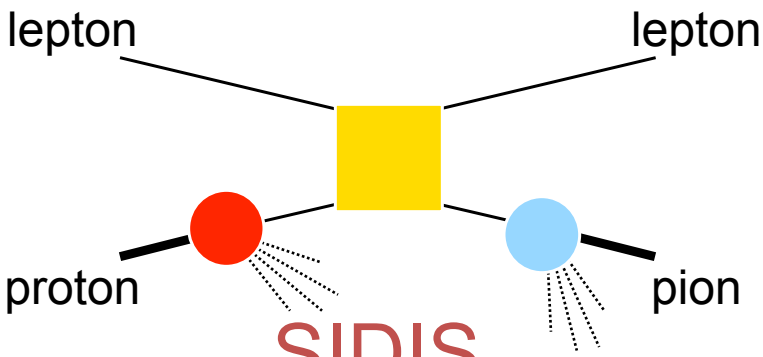
H. Gao

Leading Twist TMDs

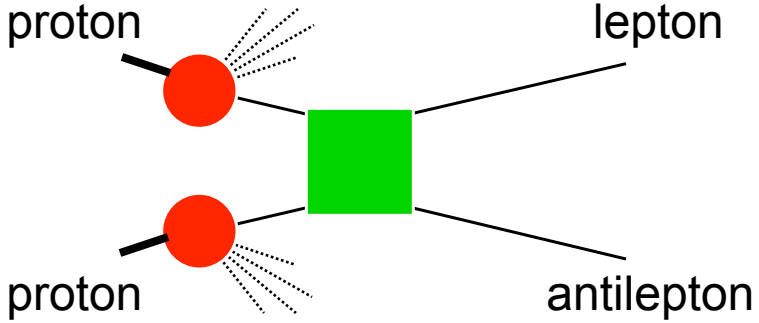
Nucleon Spin
Quark Spin

Nucleon Polarization	Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
U	f_1 = 		$h_1^{\perp}$ =  **Boer-Mulder**
L		g_1 =  **Helicity**	$h_{1L}^{\perp}$ = 
T	$f_{1T}^{\perp}$ =  **Sivers**	$g_{1T}^{\perp}$ = 	h_{1T} =  **Transversity** $h_{1T}^{\perp}$ =  **Pretzelosity**

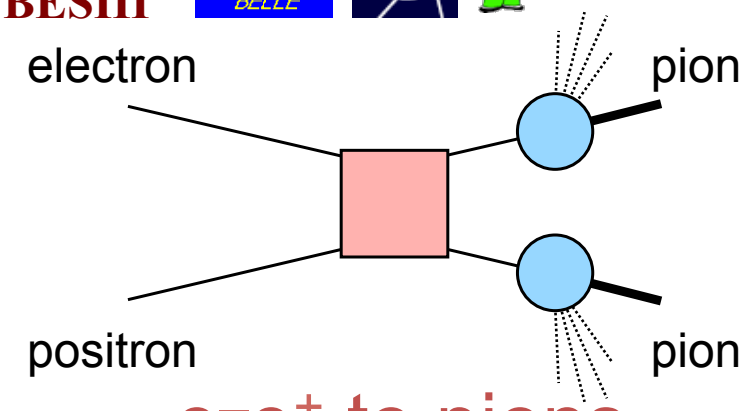
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

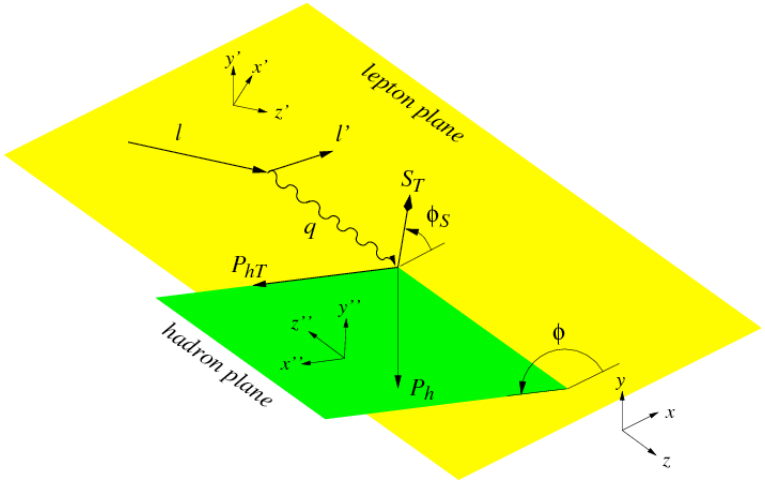
$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Jianwei Qiu (R7 Tuesday)
Rolf Ent (R7 Tuesday)

SIDIS and Structure Functions

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$, model independent. (one photon exchange approximation)



[Diehl&Sapeta EPJC2005]

$$\frac{d\sigma}{dxdydzdP_T^2 d\phi_h d\phi_S}$$

$$= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda_e \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h$$

$$+ S_L \Big[\sqrt{2\epsilon(1+\epsilon)} F_{UL}^{\sin\phi_h} \sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h} \sin 2\phi_h \Big] + \lambda_e S_L \Big[\sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} F_{LL}^{\cos\phi_h} \cos\phi_h \Big]$$

$$+ S_T \Big[(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}) \sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S)$$

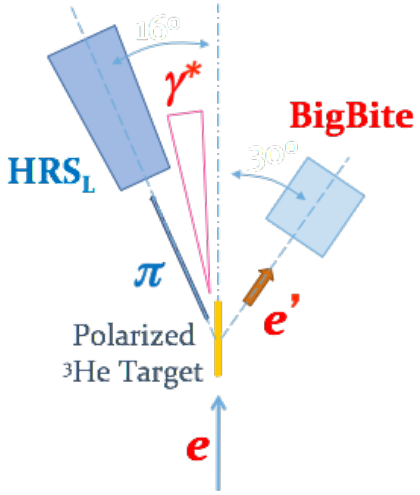
$$+ \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin\phi_S} \sin\phi_S + \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin(2\phi_h-\phi_S)} \sin(2\phi_h-\phi_S) \Big]$$

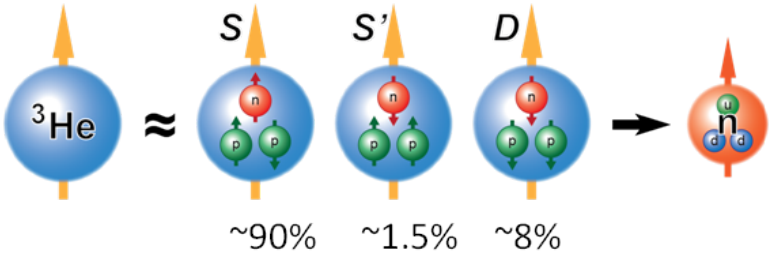
$$+ \lambda_e S_T \Big[\sqrt{1-\epsilon^2} F_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S)$$

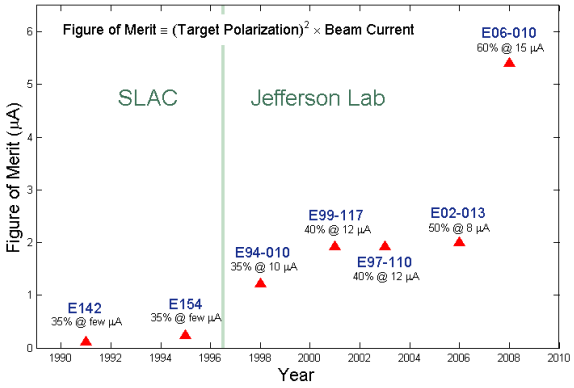
$$+ \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos\phi_S} \cos\phi_S + \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos(2\phi_h-\phi_S)} \cos(2\phi_h-\phi_S) \Big] \Big\}$$

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.

E06-010 Experiment @ Hall A



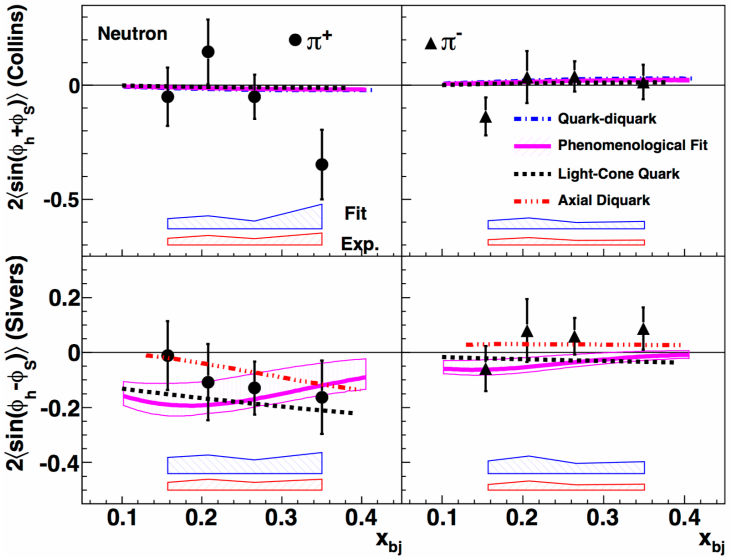




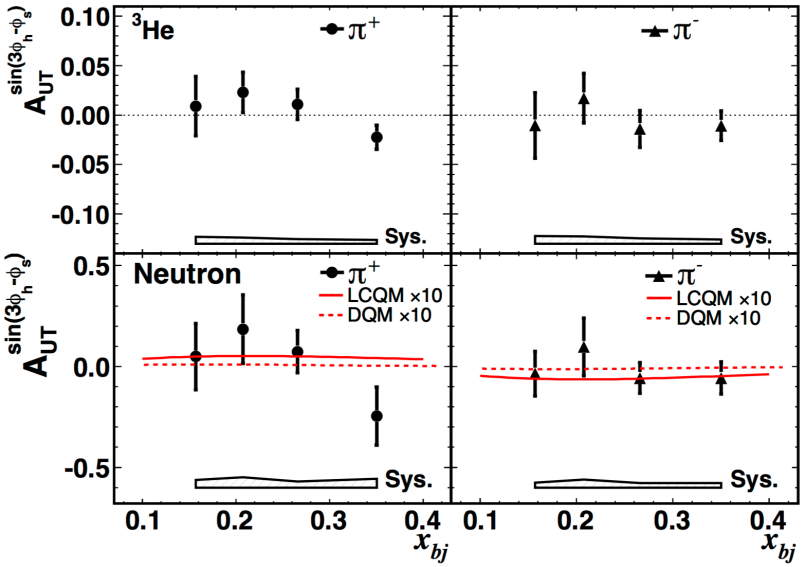
- First neutron data in SIDIS
- Electron beam energy: 5.9 GeV
  Average current: 12μA
- 40cm transversely polarized ^{3}He target, 20-min spin flip
  Average polarization: 55.4 ± 2.8% ***world record***
- BigBite at 30° as **electron** arm
  scattered electron momentum 0.6~2.5 GeV/c
- HRS at 16° as **hadron** arm
  hadron momentum ~ 2.35 GeV/c

HERMES and COMPASS
SIDIS experiments

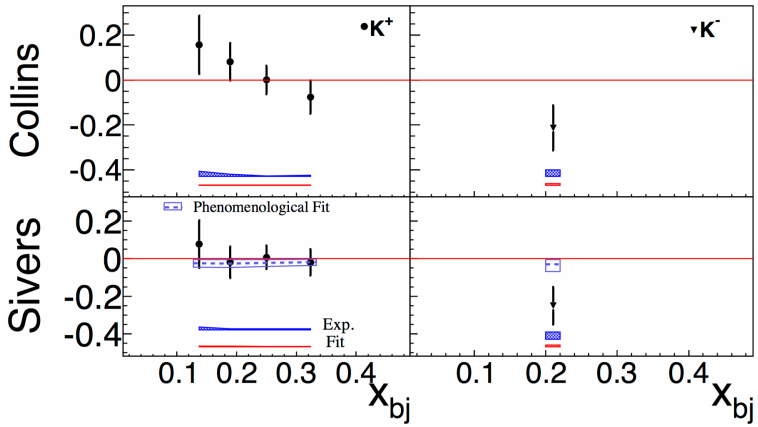
SIDIS SSA/DSA Results



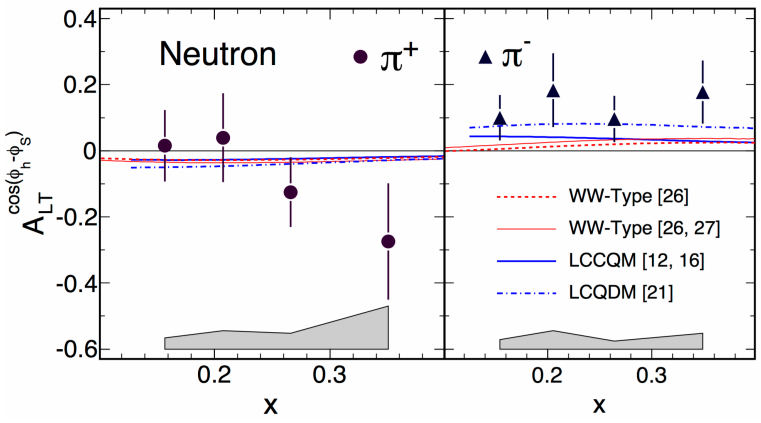
X. Qian *et al.*, PRL 107, 072003 (2011)



Y. Zhang *et al.*, PR C90, 055209 (2014)



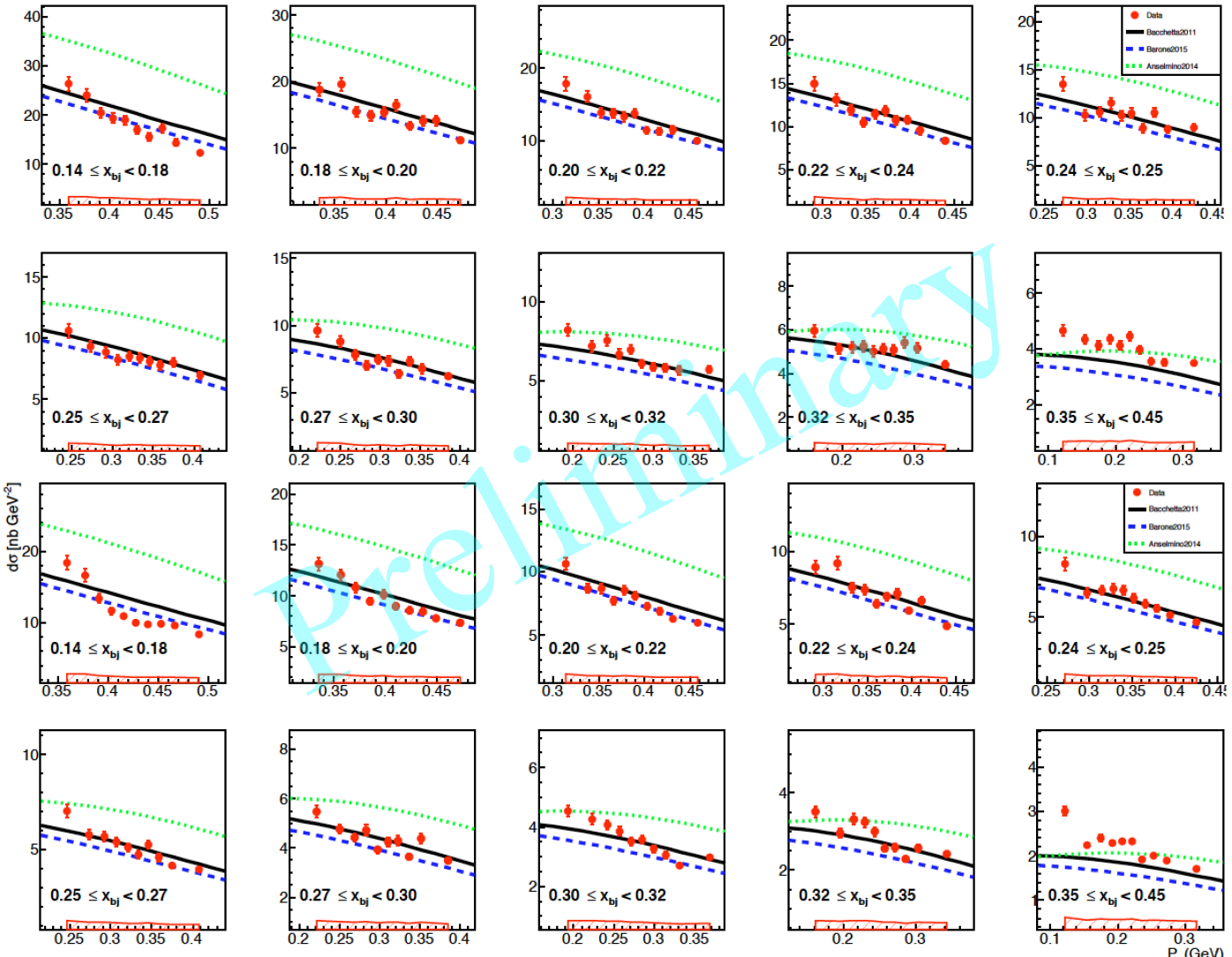
Y.X. Zhao *et al.*, PR C90, 055201 (2014)



J. Huang *et al.*, PRL 108, 052001 (2012)

Preliminary Cross Section Results

First measurement of unpolarized SIDIS differential cross section on ^{3}He target

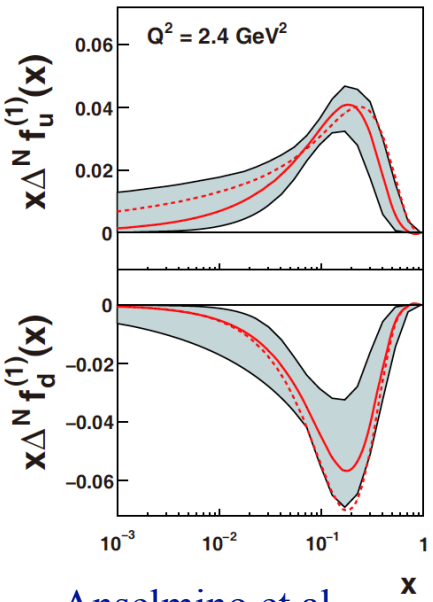


Data compared with parametrizations
Bacchetta2011, Anselmino2014, and Barone2015

X. Yan *et al.*,
To be submitted

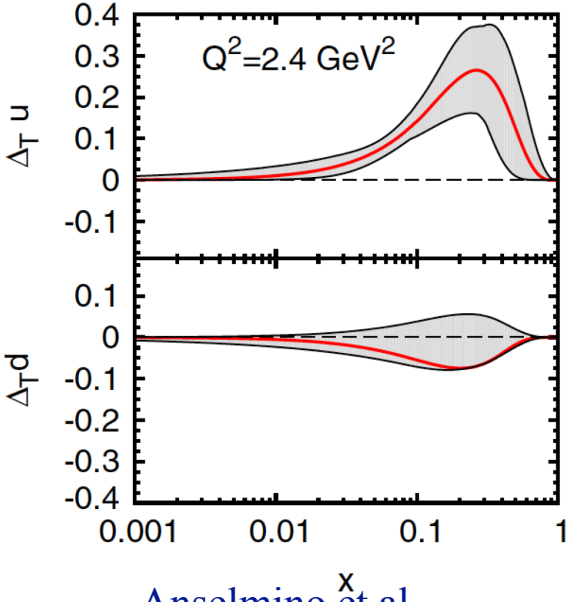
Present Status On TMD Extractions

Sivers



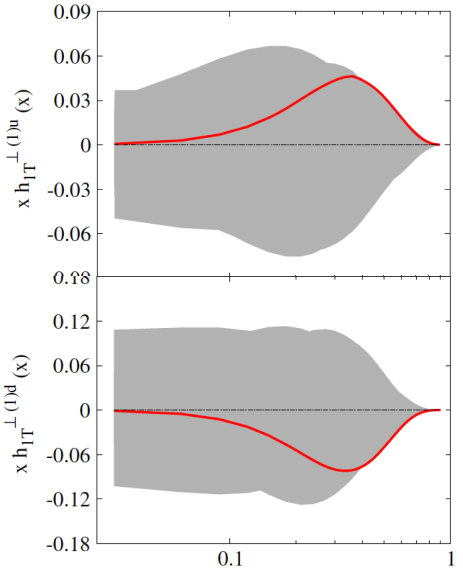
Anselmino et al,
EPJA39, 89 (2009)

Transversity



Anselmino et al,
PRD92, 114023 (2015)

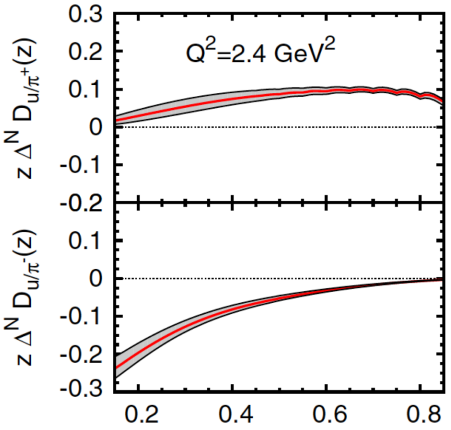
Pretzelosity

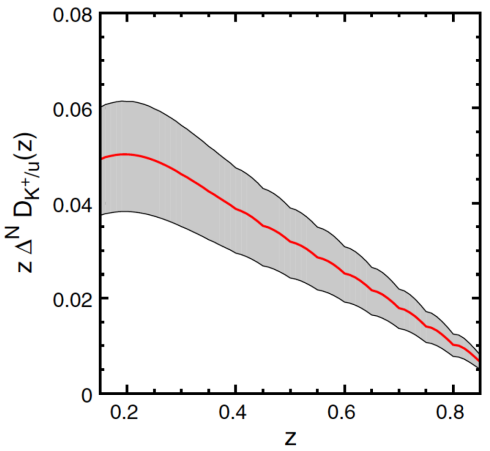


Lefky et al,
PRD91, 034010 (2015)

Collins fragmentation

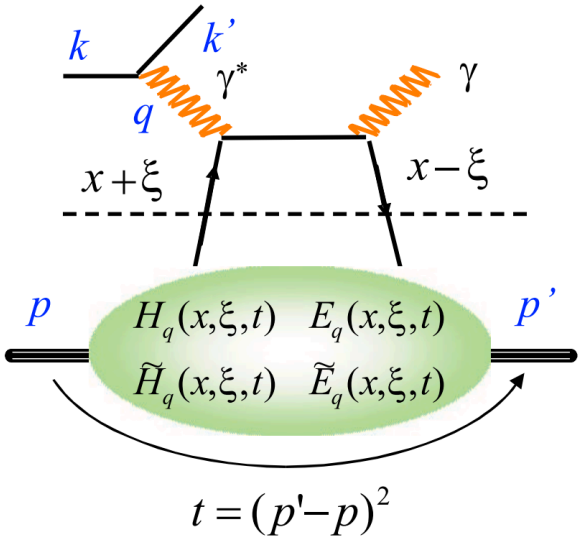
Anselmino et al,
PRD92, 114023 (2015)
PRD93, 034025 (2016)





Access GPDs through Hard Processes

Deeply Virtual Compton Scattering (DVCS)



Interference with Bethe-Heitler (BH) process gives access to real and imaginary part of DVCS amplitude

$$d\sigma \propto |\mathcal{T}|^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I}$$

$$\mathcal{I} \propto \frac{-e_\ell}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

e.g.:

$$c^{\mathcal{I}}_{1,\rm unpol.} \propto \left[F_1\,\mathfrak{Re}\,\mathcal{H} - \frac{t}{4M_p^2}F_2\,\mathfrak{Re}\,\mathcal{E} + \frac{x_{\rm B}}{2-x_{\rm B}}(F_1+F_2)\,\mathfrak{Re}\,\tilde{\mathcal{H}}\right]$$

Access different GPDs

$$d\sigma_{LU} = \sin\phi\cdot\mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

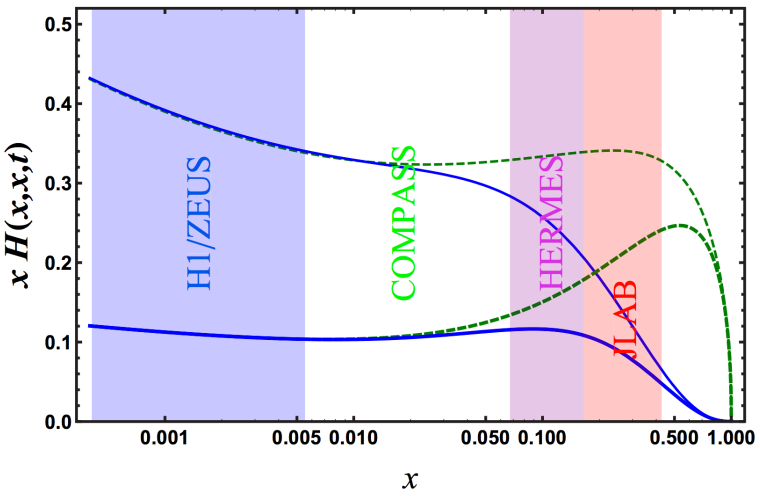
$$d\sigma_{UL} = \sin\phi\cdot\mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_Bk F_2\tilde{\mathcal{E}}\ldots\}d\phi$$

$$d\sigma_{LL} = (A + B\cos\phi)\cdot\mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

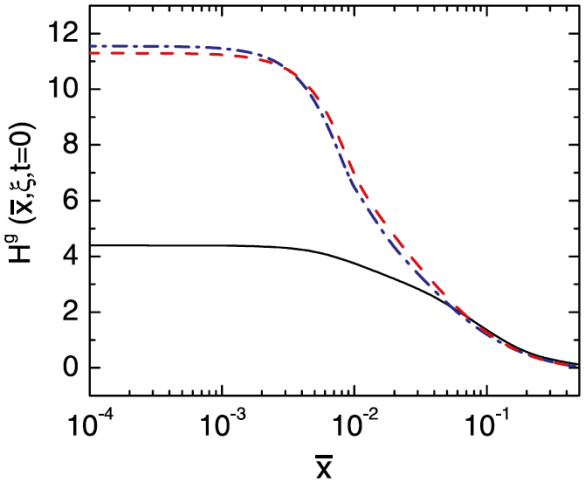
$$d\sigma_{UT} = \cos\phi\cdot\mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

Alternative processes: deeply virtual meson production (DVMP), double DVCS, timelike Compton scattering (TCS)… **(A. Camsonne R7)**

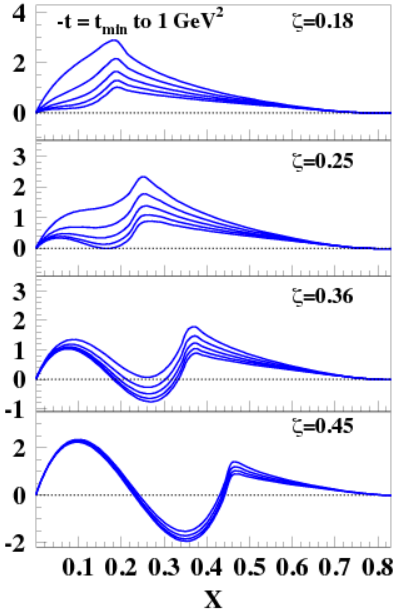
Global Analysis of GPDs

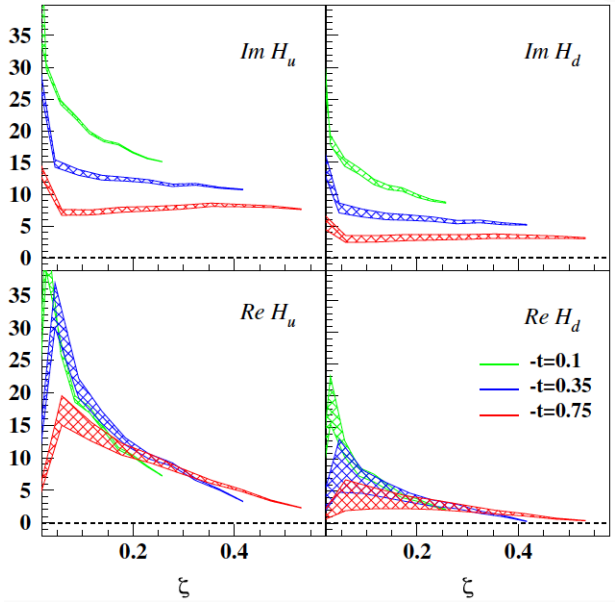


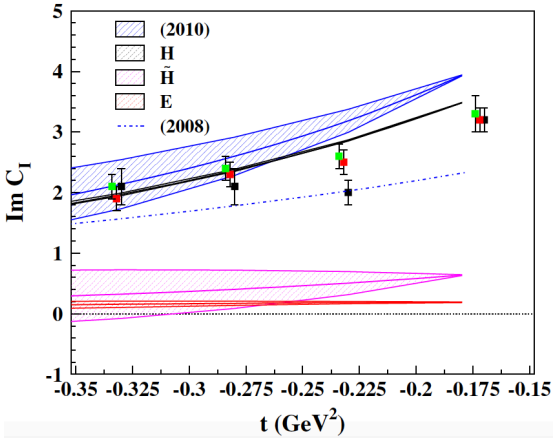
Kumerički and Müller NP B841, 1(2010)



Goloskokov and Kroll, EPJ C53, 367(2008)



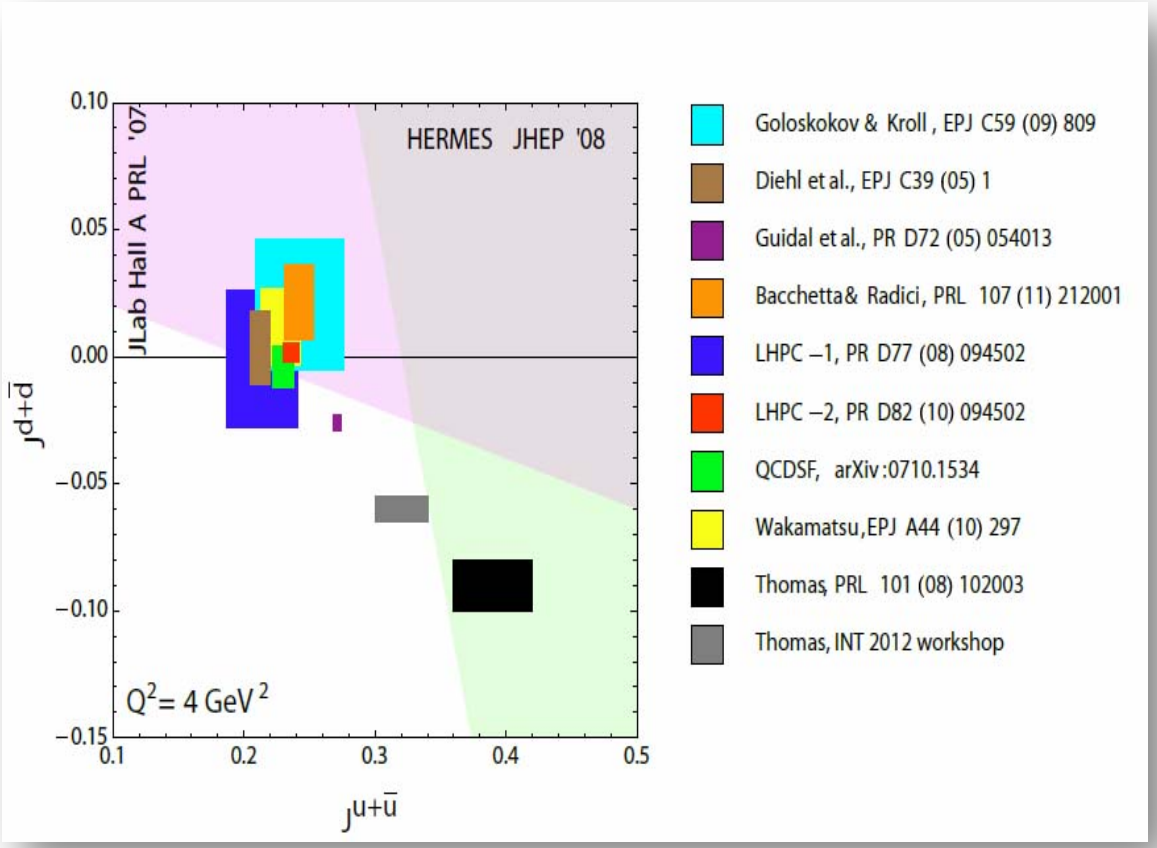




Goldstein et al., PR D84, 034007(2011)

Quark Angular Momentum

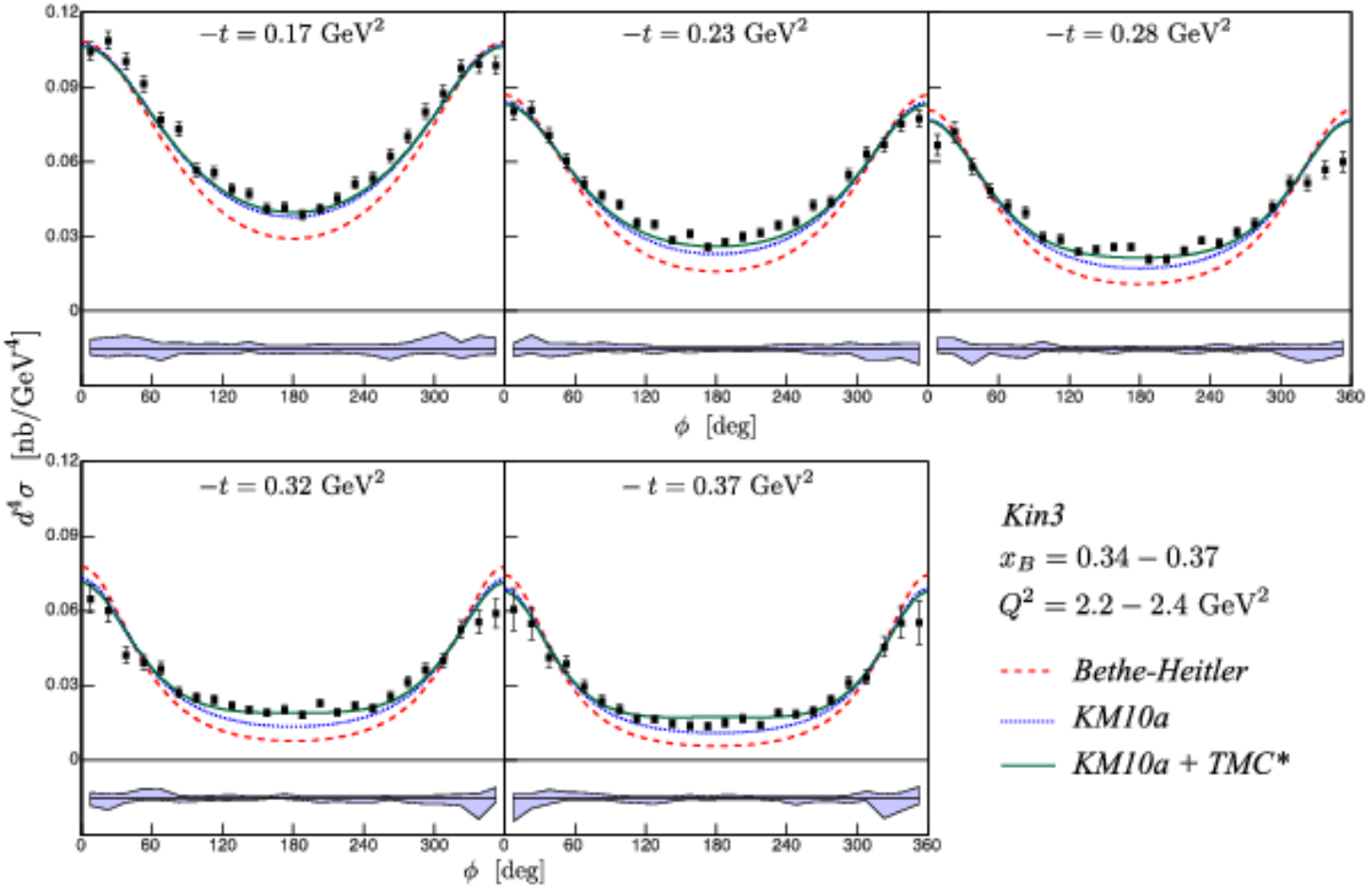
Ji's sum rule: $$J^q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,t)+E^q(x,\xi,t)] = \frac{1}{2}\Delta\Sigma + L^q$$



→ **Access to quark orbital angular momentum with GPDs**

Recent Results of DVCS from Hall A @ JLab

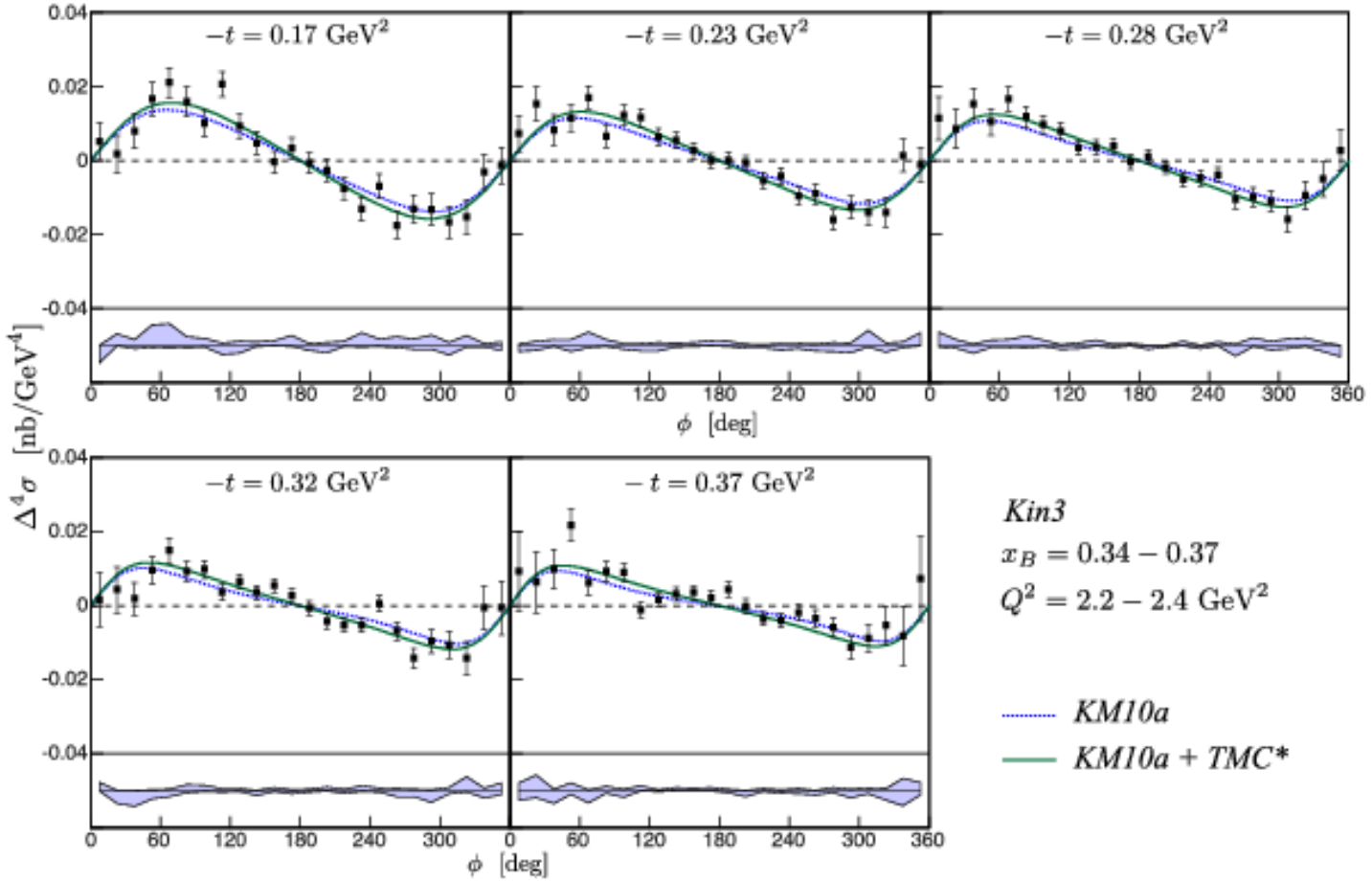
Unpolarized cross section



M. Defurne *et al.*, Phys. Rev. C 92, 055202 (2015).

Results of DVCS in Hall A

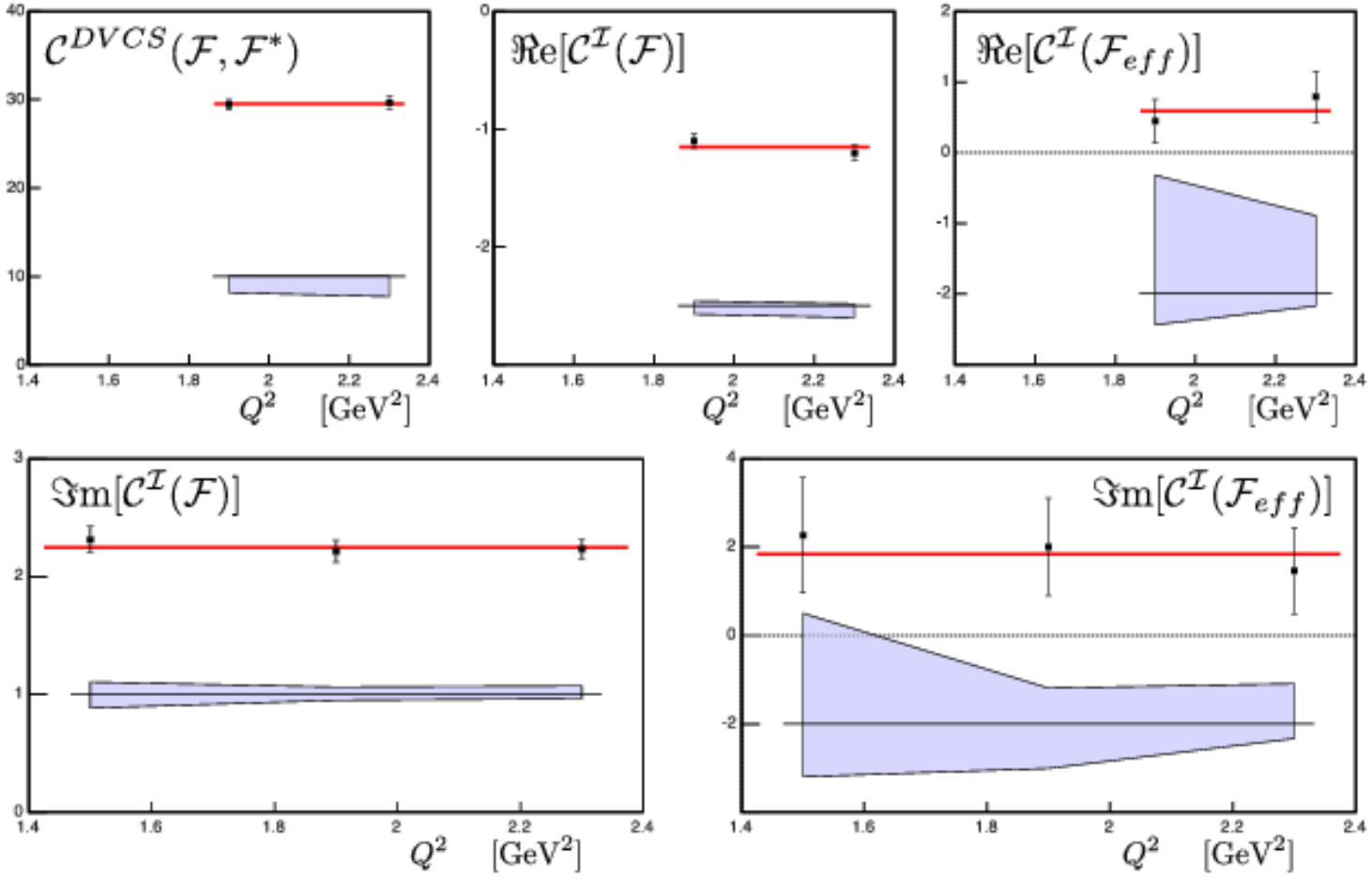
Polarized cross section



M. Defurne *et al.*, Phys. Rev. C 92, 055202 (2015).

Results of DVCS in Hall A

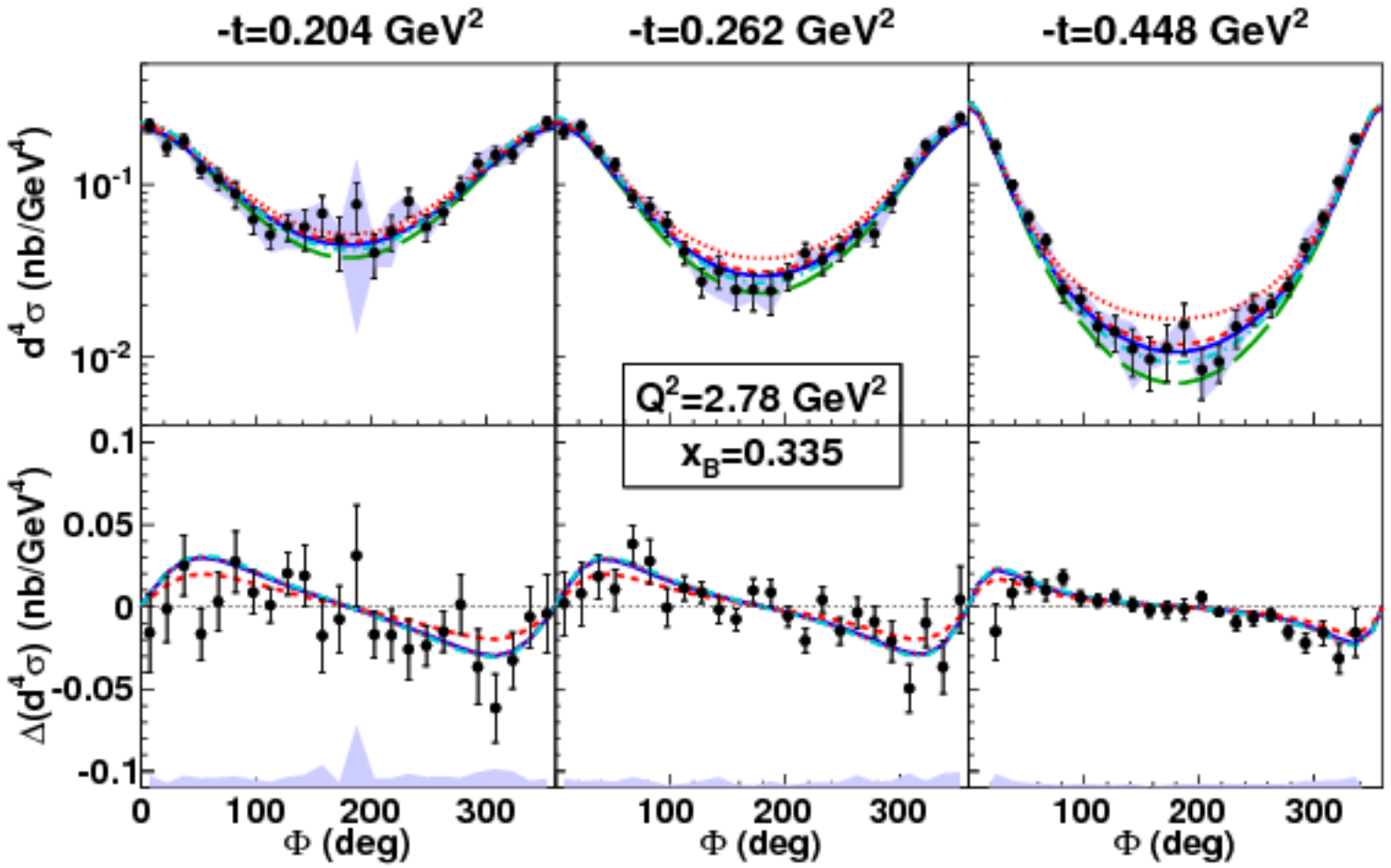
Compton form factors (CFFs)



M. Defurne *et al.*, Phys. Rev. C 92, 055202 (2015).

Recent Results of DVCS from Hall B @ JLab

Unpolarized and polarized cross section

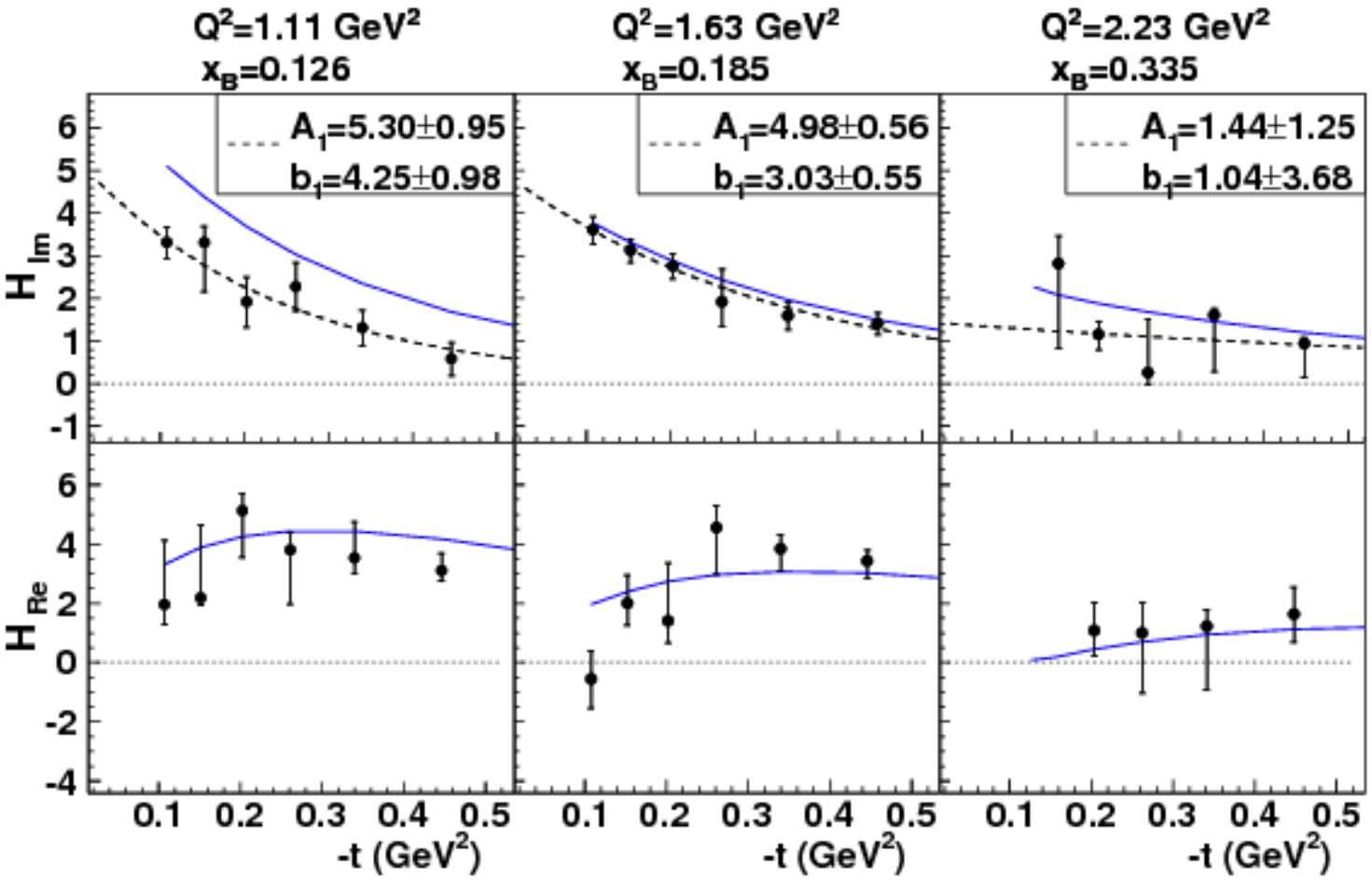


H.S. Jo *et al.*, Phys. Rev. Lett. 115, 212003 (2015).

H.S. Jo R7 Thursday

Results of DVCS from Hall B

Compton form factors (CFFs)



H.S. Jo *et al.*, Phys. Rev. Lett. 115, 212003 (2015).

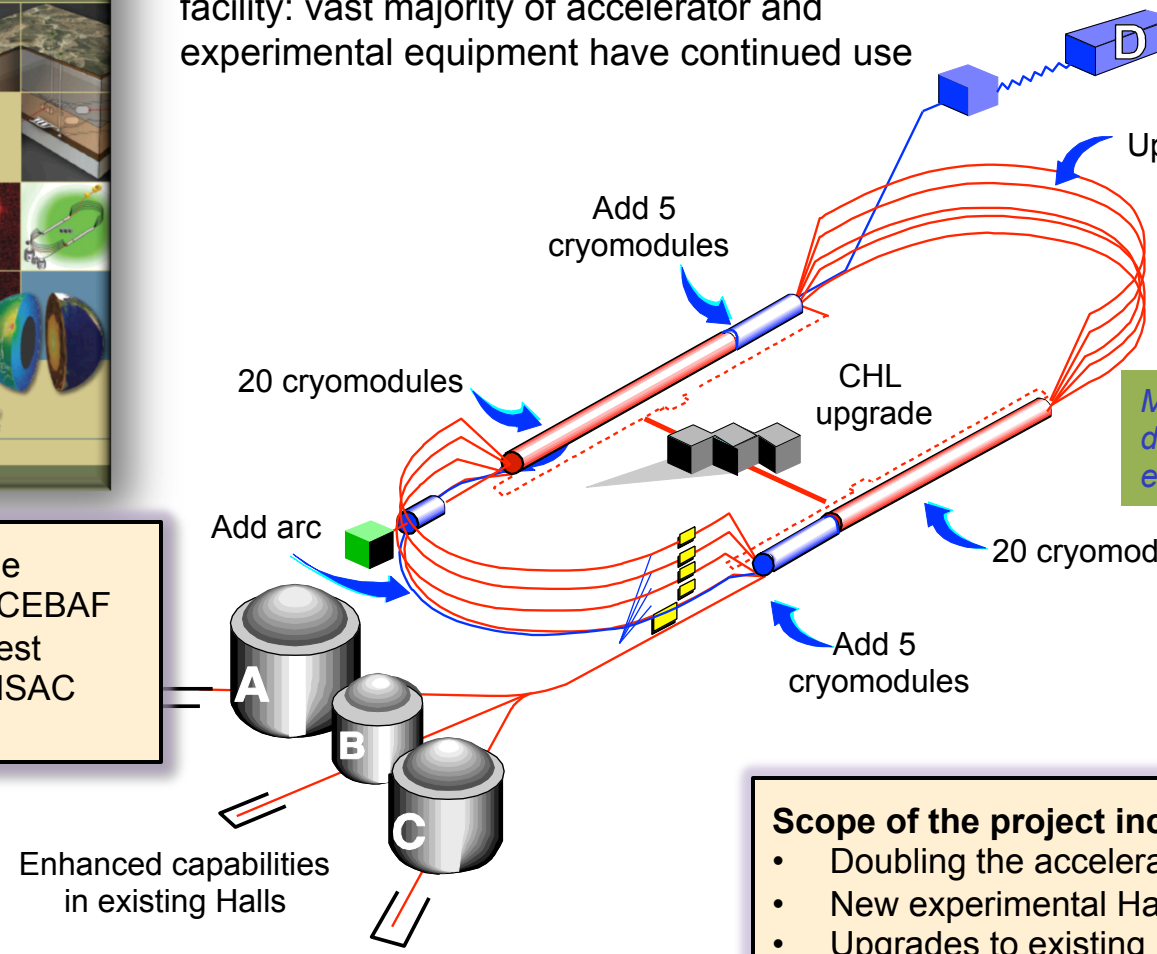
H. Gao

H.S. Jo R7 Thursday

12 GeV Upgrade and TMD/GPD at JLab

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



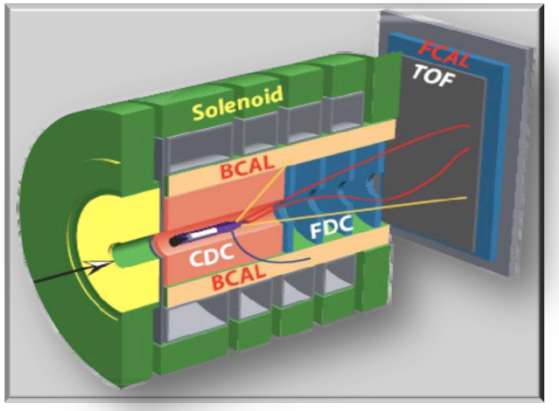
*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

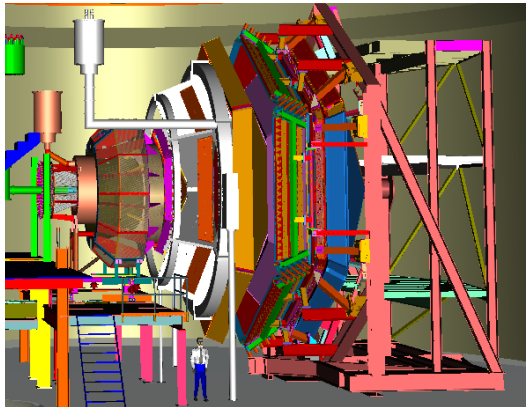
Scope of the project includes:

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

12 GeV Upgrade Physics Instrumentation

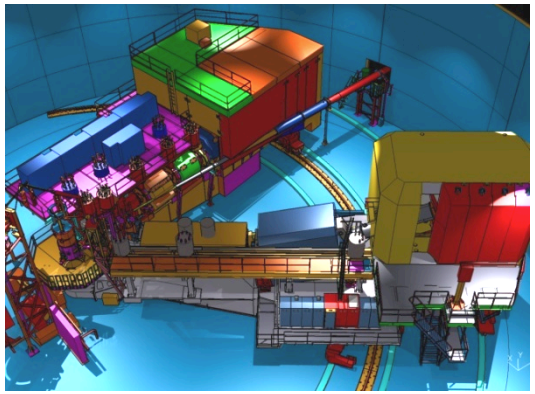
GLUEx (Hall D): **exploring origin of confinement by studying hybrid mesons**

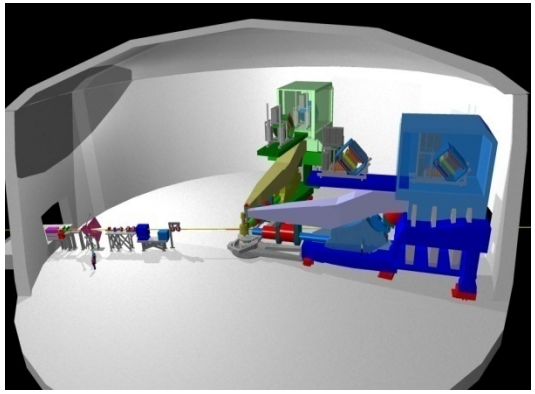




CLAS12 (Hall B): **understanding nucleon structure via generalized parton distributions**

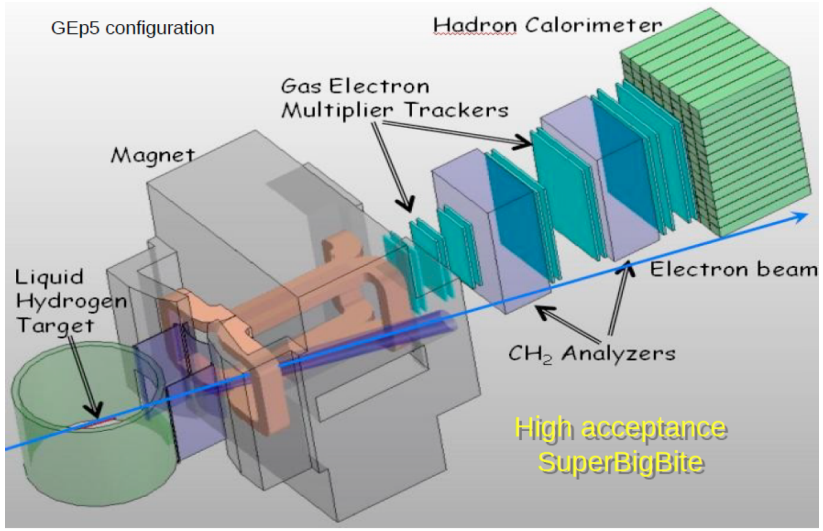
SHMS (Hall C): **precision determination of valence quark properties in nucleons and nuclei**





Hall A: **nucleon form factors (Super BigBite),**
& future new experiments like Moller & SoLID

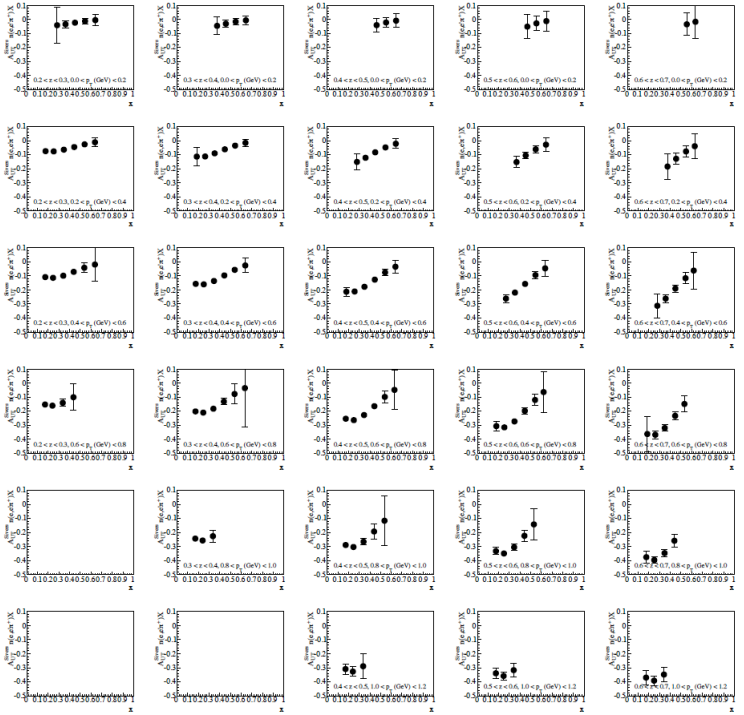
SuperBigBite Spectrometer @ Hall A

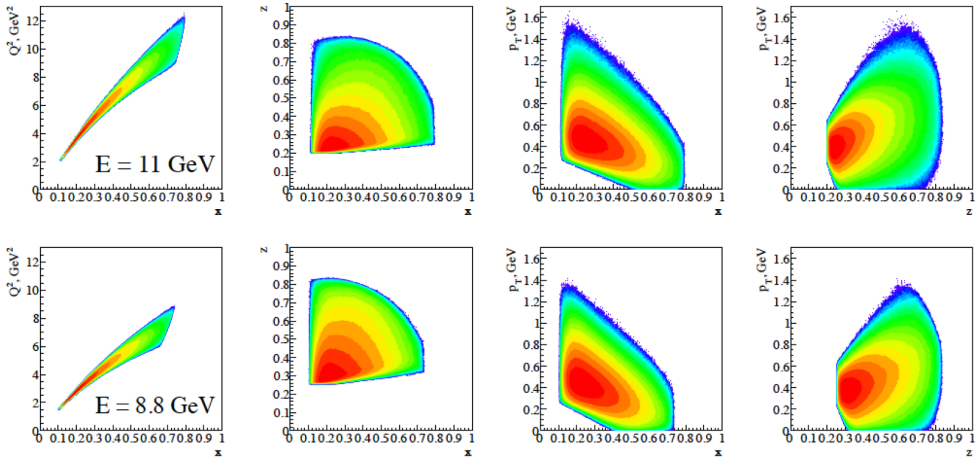


E12-09-018: 64 days

neutron (^{3}He) target

3D mapping example

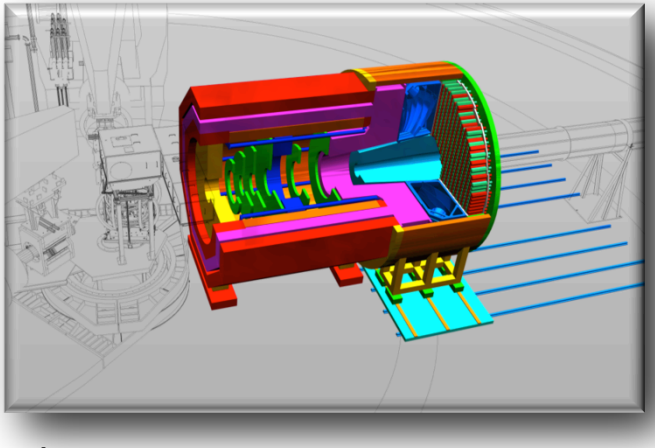




Solenoidal Large Intensity Device (SoLID) Physics

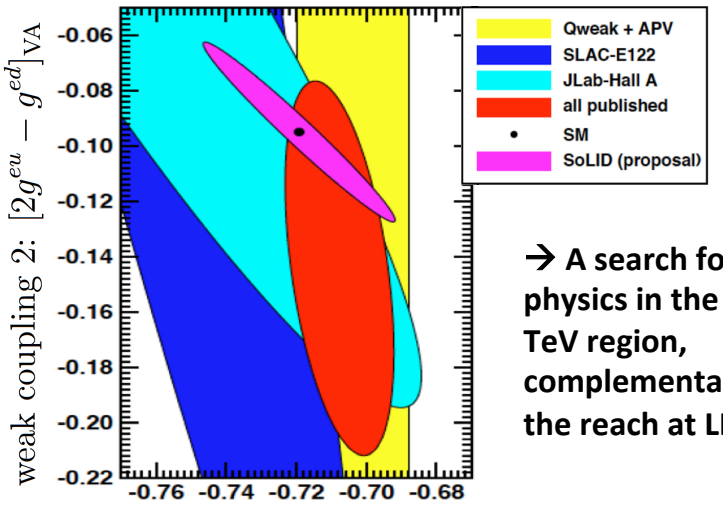
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage



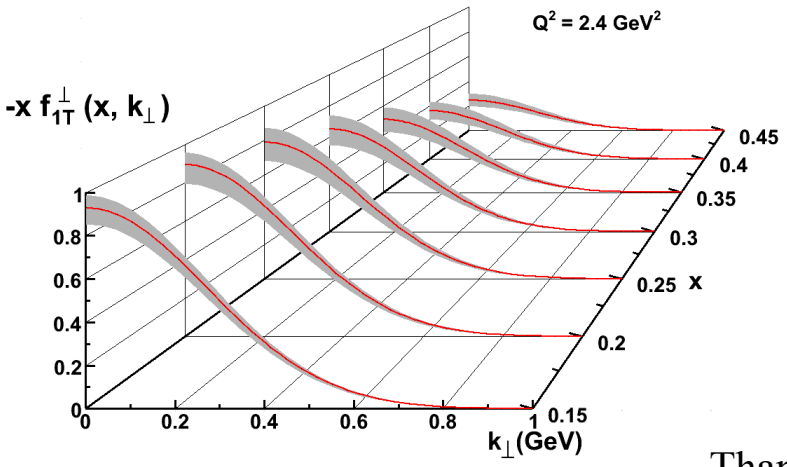
→ multi-purpose program to maximize the 12-GeV science potential

2) Precise determination of the electroweak couplings

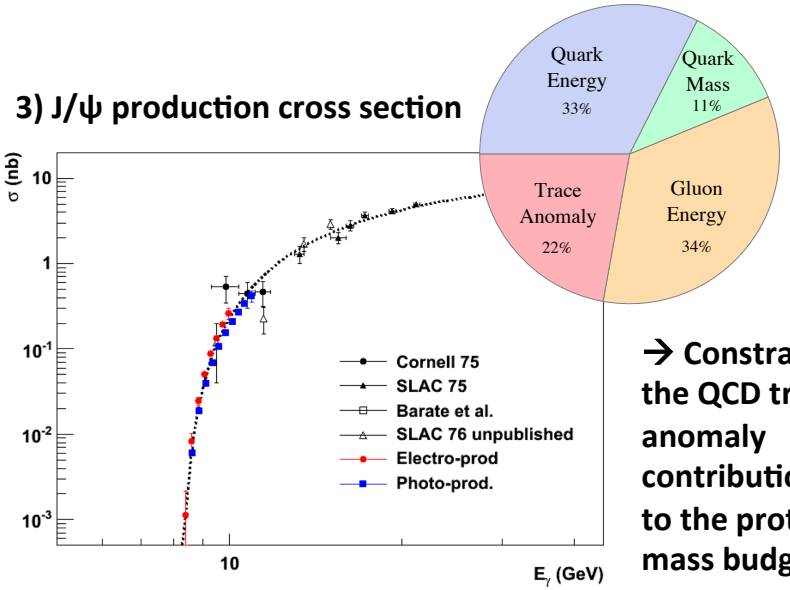


→ **A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.**

1) Precision in 3D momentum space imaging of the nucleon



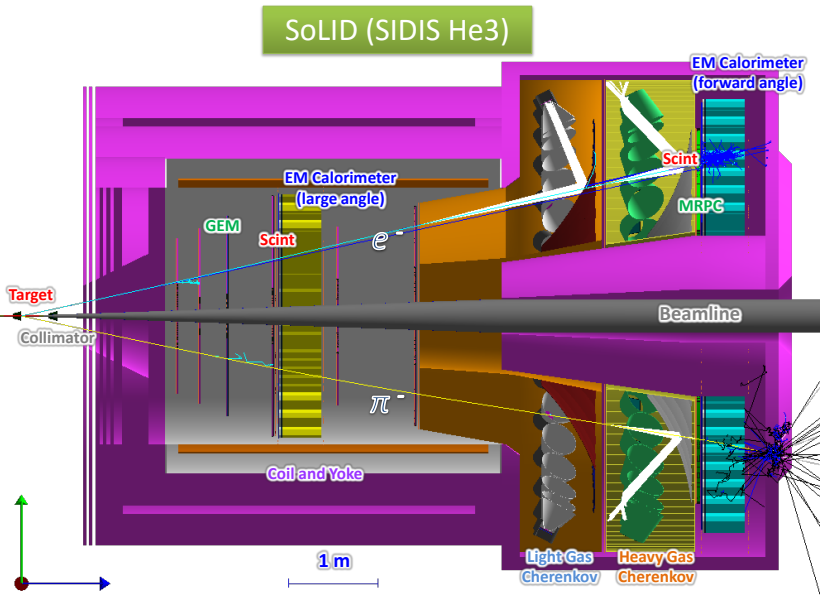
3) J/ψ production cross section

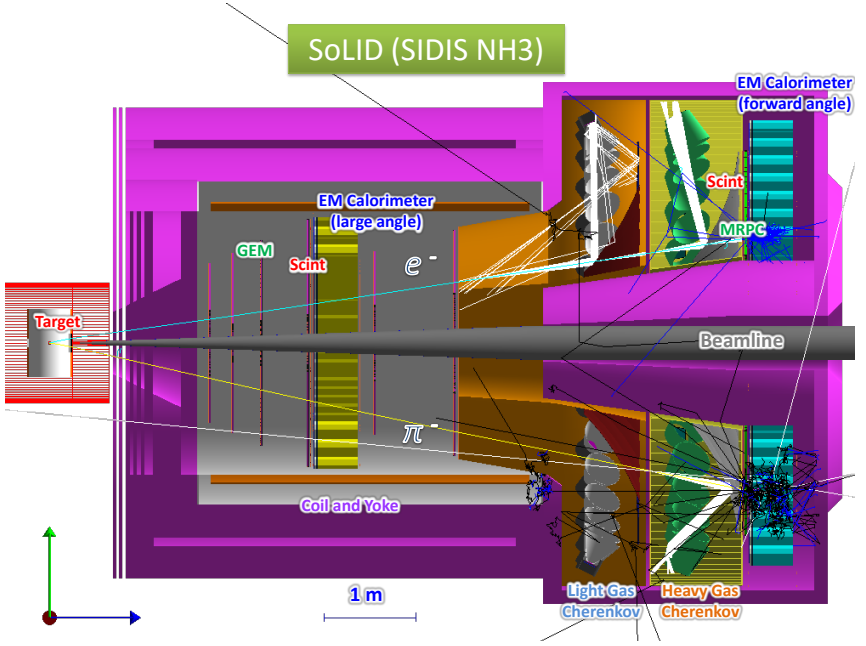


→ **Constrain the QCD trace anomaly contribution to the proton mass budget**

Thanks to Rolf Ent and Thia Keppel

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV





E12-10-006: Single Spin Asymmetry on Transverse ^{3}He @ 90 days, **rating A**

E12-11-007: Single and Double Spin Asymmetry on ^{3}He @ 35 days, **rating A**

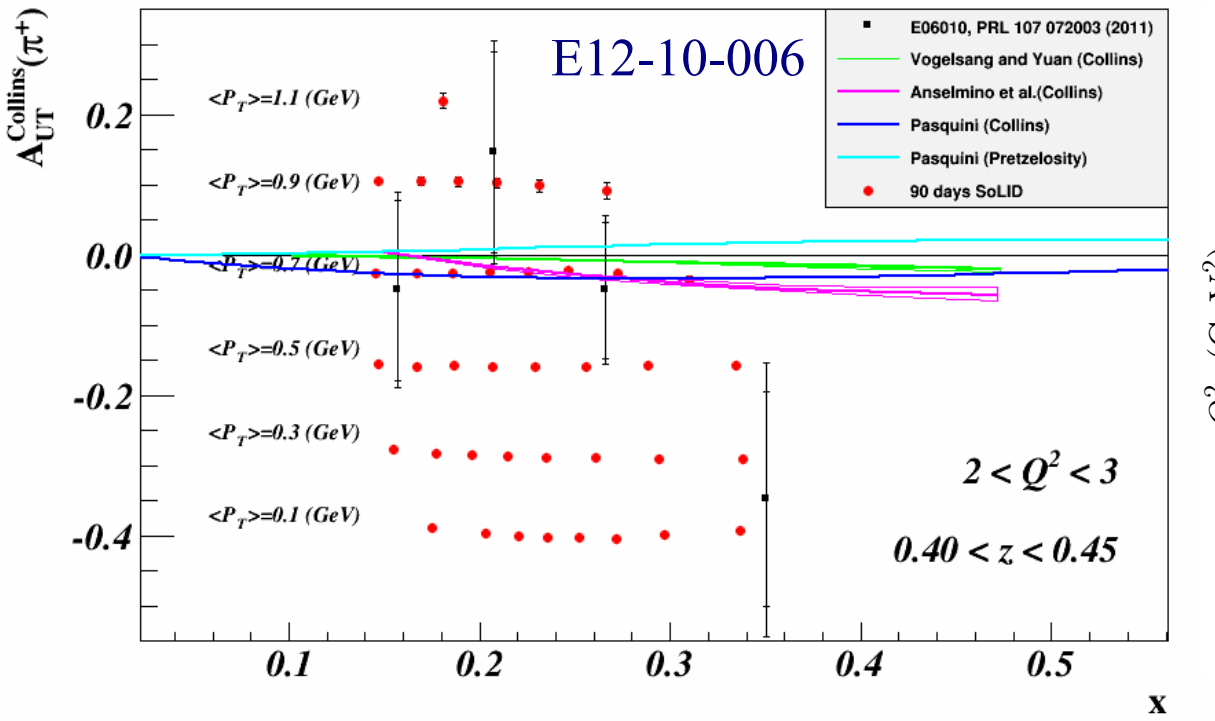
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

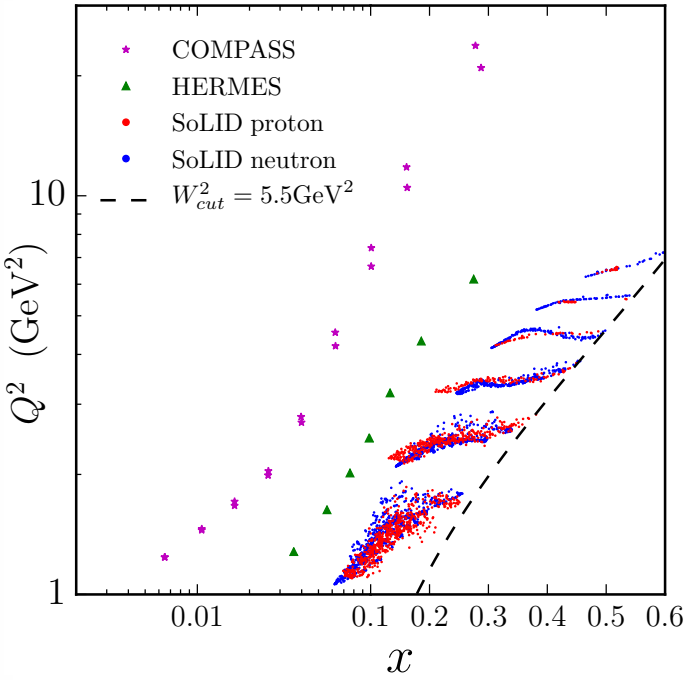
Three run group experiments approved: TMDs, GPDs, and

much more

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

SoLID-SIDIS Projected Data





- Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.
- z ranges from 0.3 ~ 0.7, only one z and Q^2 bin of 11/8.8 GeV is shown here. π^+ projections are shown, similar to the π^- .

E12-10-006 Spokespersons: Chen, Gao (contact), Jiang, Qian and Peng

H. Gao **X. Qian et al in PRL 107, 072003**

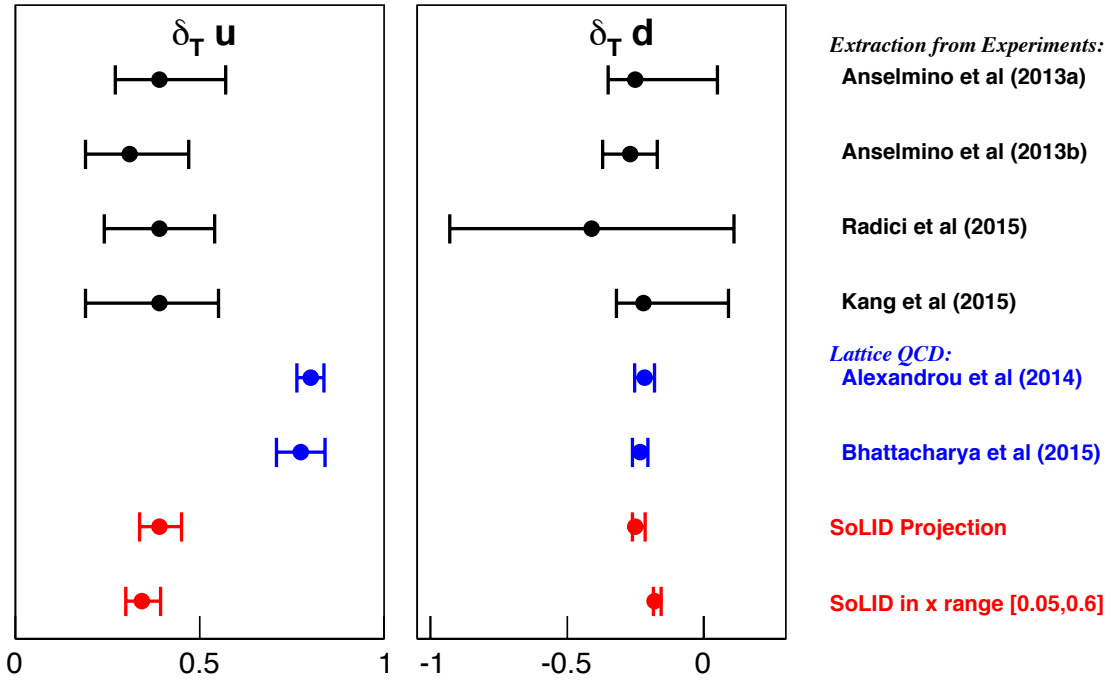
SoLID Impact on Tensor Charge

Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = \delta_T q \bar{u}(P,S) i\sigma^{\mu\nu} u(P,S) \quad \delta_T q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x)\right] \mathrm{d}x$$

A fundamental QCD quantity. Matrix element of local operators.
Moment of transversity distribution. Valence quark dominant.
Calculable in lattice QCD.

SoLID impact



Not shown are various other Predictions on tensor charge

Hall C SIDIS Program (typ. x/Q^2 ~ constant)

[R. Ent, DIS2016]

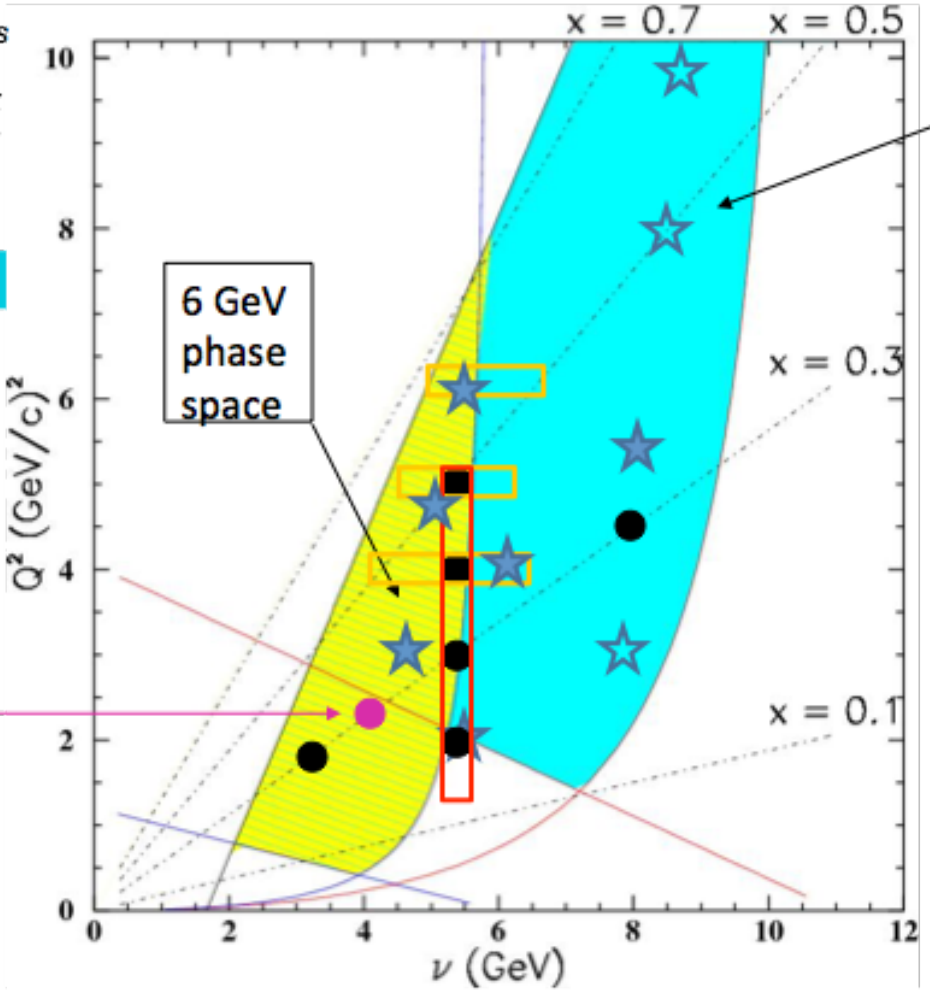
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017 & E12-09-002

Parasitic with E12-13-010

E00-108 (6 GeV)



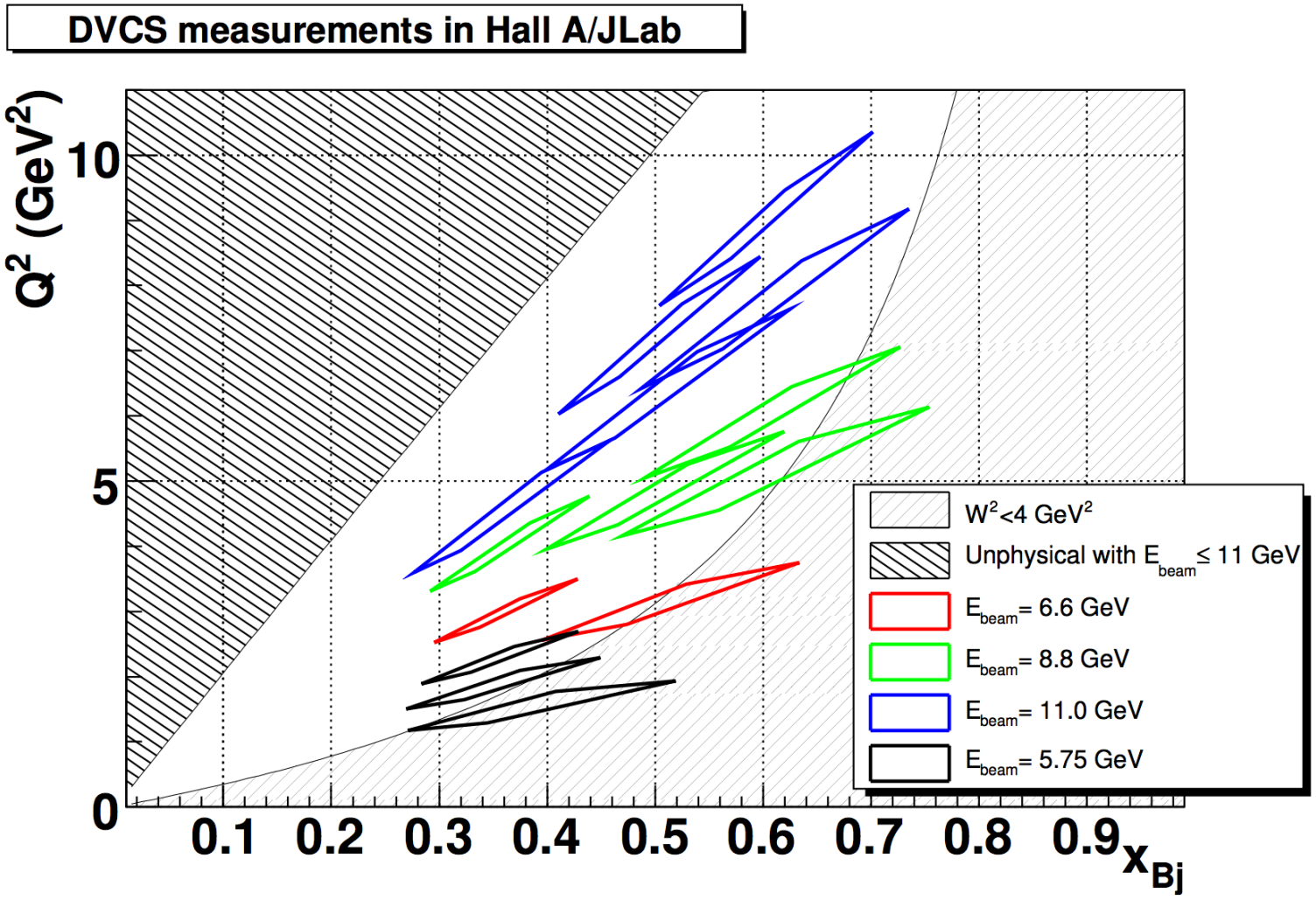
Charged pions:

E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

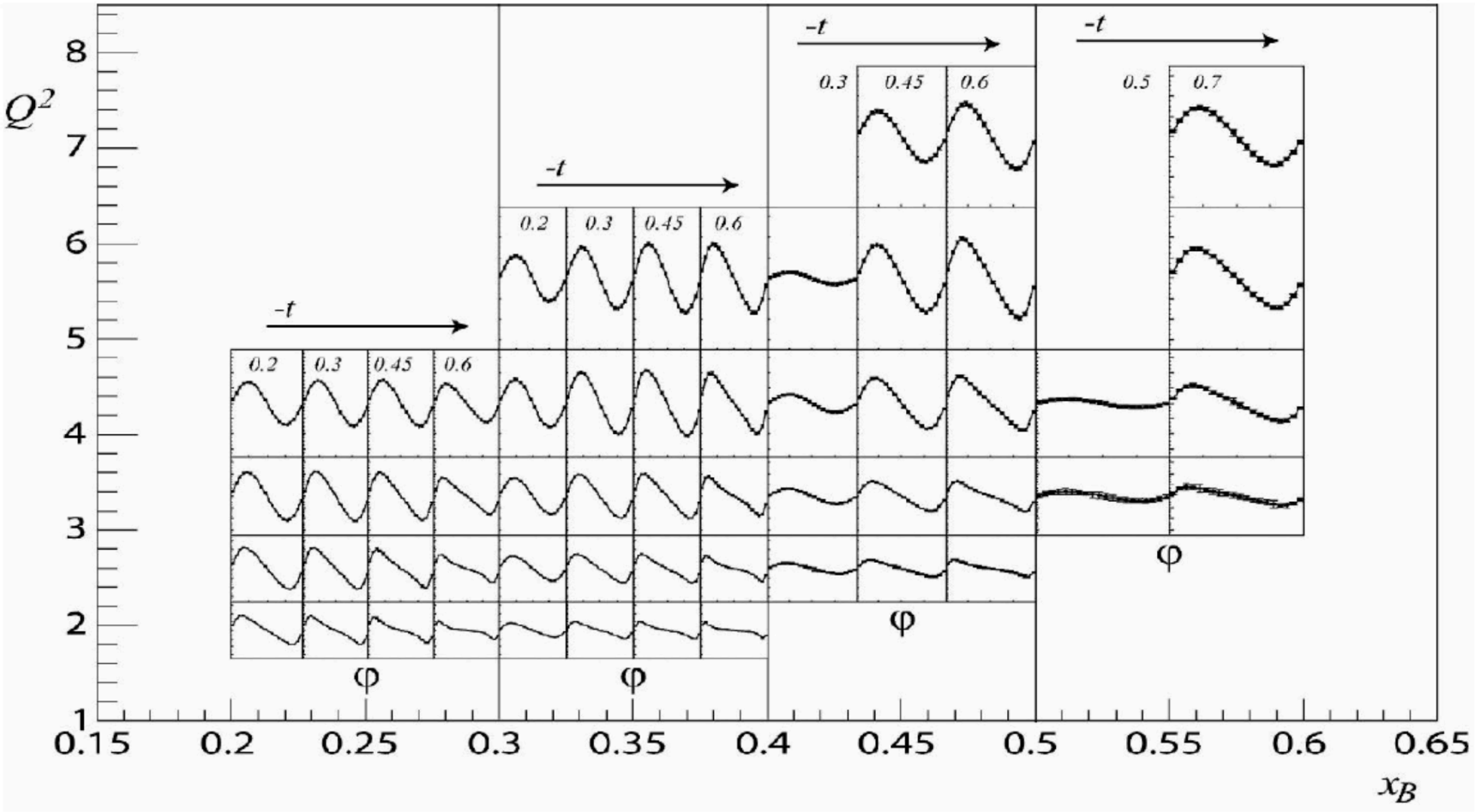
E12-09-002
+ scans in z

GPDs: Hall A E12-06-114 Experiment



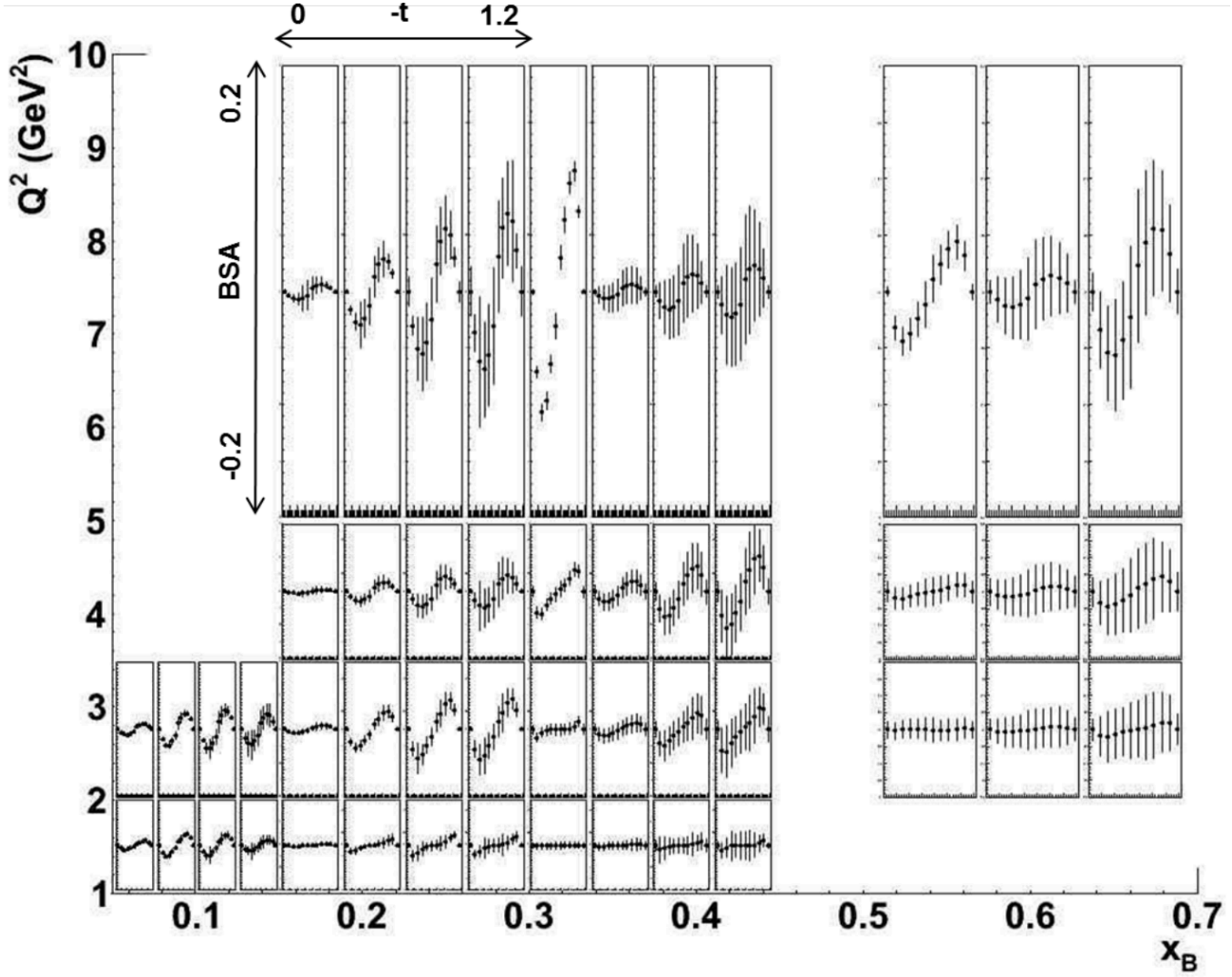
A. Camsonne, R7 Thursday

Hall B E12-06-119 Experiment on DVCS

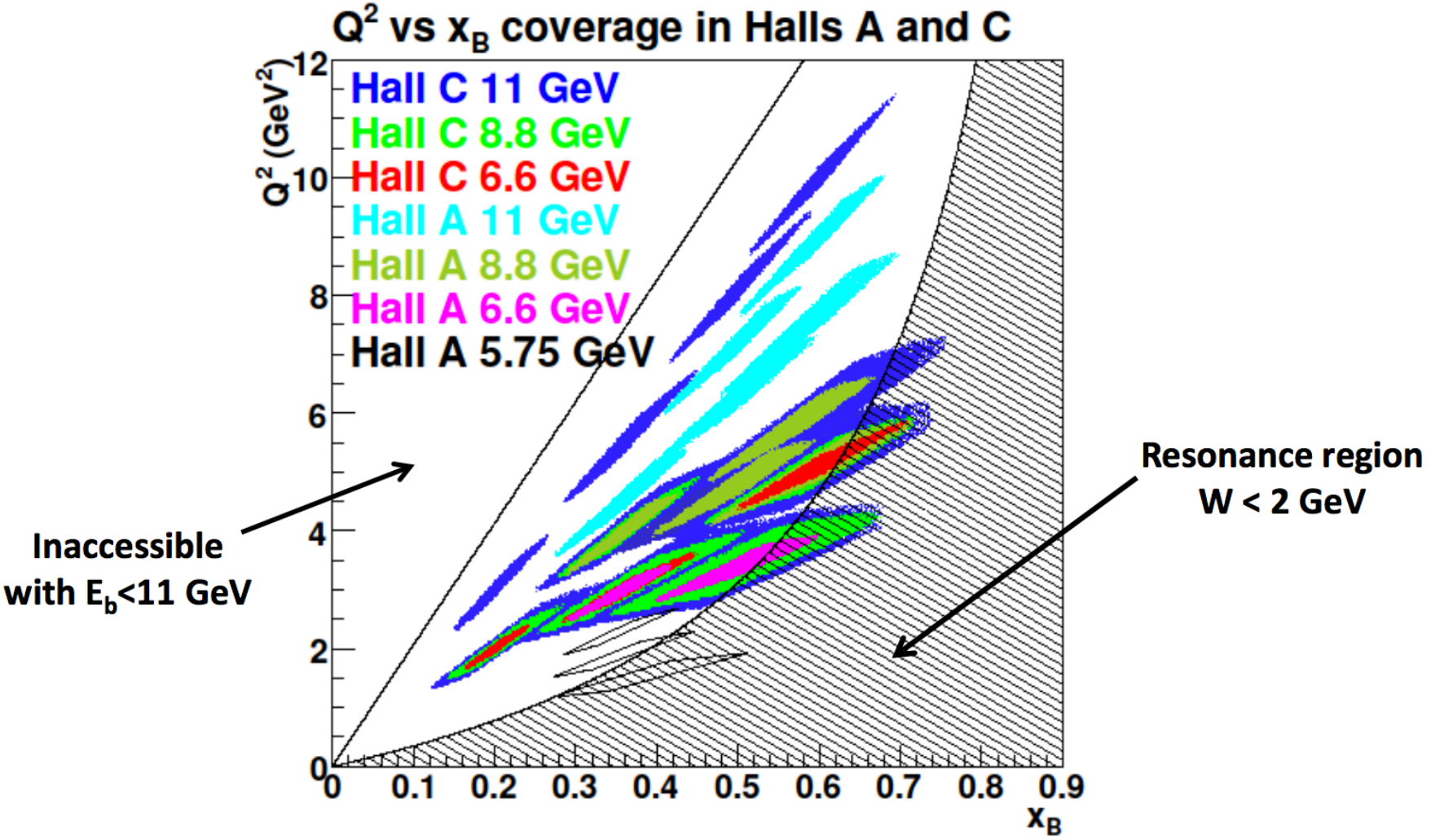


H.S. Jo R7 Thursday

Hall B E12-11-003 Experiment on DVCS



Hall C E12-13-010 Experiment on DVCS



Summary

- Spin remains important and puzzling for nucleon
- Three-dimensional imaging of nucleon helps solve this remaining puzzle, and uncover the rich dynamics of QCD
- Rich TMD and GPD Physics programs at 12-GeV Jlab
  - SBS in Hall A on TMD, and Hall C on SIDIS and GPD
  - SoLID SIDIS program with unprecedented precision on TMDs, and a program on GPD is shaping up (A. Camsonne R7)
  - CLAS12 extensive GPD and TMD programs

Thanks to K. Allada, J.-P Chen, R. Ent, C. Keppel, T.-B. Liu, Z.-E. Meziani, A. Prokudin, N. Sato, P. Souder, Z. Ye, X.F. Yan, and Z. Zhao, and others

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